ECONOMIC EVALUATION OF SEAWATER DESALINATION:

A CASE STUDY ANALYSIS OF COST OF WATER PRODUCTION FROM SEAWATER DESALINATION IN SAUDI ARABIA

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Abstract

As a result of the increasing scarcity of freshwater resources worldwide, many countries have resorted to the use of unconventional sources, of which seawater desalination is the most significant, for meeting the supply-demand gap. However, despite the recorded advances in desalination technologies of recent decades, desalination remains a very expensive operation and operators will be greatly assisted if reliable means of predicting the costs are available to aid effective decision making during planning of new plants or the operation of existing plants. To achieve this, it is important to fully understand the factors that contribute to desalination costs, which could then be used to develop appropriate models for predicting costs that can support budgeting and/or cost reductions decision making. Consequently, this project has investigated the development of such models for predicting monthly production costs using data from 16 operational plants in Saudi Arabia. Monthly and annual data spanning 2001 – 2010 were collected on total water production, type of desalination technique, sea water salinity, product water salinity, energy consumption, and total (capital and operational) unit cost of water production. Because of the way in which the data were archived, some of the variables only had the annual totals for some of the years, which made them unsuitable for the monthly scale adopted for the analyses. Consequently, disaggregation schemes based on several variants of the method of fragments widely used in hydrological studies were used to obtain monthly data from the annual data. Exploratory analysis showed that the monthly costs correlated most with the total water production, which then formed the lone independent variable for various tested regression model formulations. In general, an inverse regression model performed best during both calibration and validation. To enhance the usefulness of the predictive model for decision making, uncertainty limits of the predictions were constructed using a Monte Carlo simulation approach involving the seasonal, lag-1 autoregressive generation of equally likely realisations of the available historic records that have been transformed to remove the skewness. Extensive testing of the data generation technique showed that the assumed lag-1 auto-regressive dependence structure was adequate. This study thus provides for the first time a predictive model for costs of desalination in Saudi Arabia and its uncertainty range for effective budgeting and operational management. Although the models were developed using Saudi Arabia data, the fact that only one independent variable was used means that the replication of the methodology in other desalination-intensive countries can be readily carried out.

Dedication

To my mother, my wife and my children

Rana, Khalid, Jana, Gala, and Abdulaziz

Acknowledgements

In the beginning I am grateful to Almighty Allah, who is merciful and favoured me to accomplish this research.

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Glossary of Abbreviations

A	Amortization or annuity factor
BH	Brine heater of multi-stage flash desalination technology
CF_0	Capital investment cost
$DNCF_t$	Discount net cash flow for year t
DPB	Discount payback period
DT	Type of desalination techniques
EAC	Equivalent annual cost
EC	Unit energy consumption
ECRA	Electricity &Co-Generation Regulatory Authority
ED	Electrodialysis desalination technology
EMC	Equivalent monthly capital cost
E_{st}	The efficiency of the steam turbine generator, %
GCC	Gulf Cooperation Council Counties
GDP	Gross Domestic Product
GOR	The ratio between the weight of distilled water produced and steam
H_{su}	The enthalpy of inlet steam to the desalination process (kJ/kg)
H_{sc}	The enthalpy of the steam at the steam turbine extraction (kJ/kg)
m_s	Weight of steam (kilograms)
m_d	Weight of distilled water produced (kilograms)
MED	Multi-effect desalination technology
MOF	Method of fragments
MSF	Multi-stage flash desalination technology
MVC	Mechanical vapour compressor desalination technology
NF	Nanofiltration desalination technology
NPV	Net present value
NWC	National Water Company
P	Total water production
PSV	Present value of the Salvage Value
PV	Present value
PWTDS	Product water total dissolved solid
R^2	Coefficient of determination
RO	Reverse osmosis desalination technology
ROBW	Reverse osmosis desalination technology of brackish water
ROSW	Reverse osmosis desalination technology of sea water
SR	Saudi Riyals
SV	Salvage value
SWCC	Saline Water Conversion Corporation
SWTDS	Sea water total dissolved solid
TUC	Total unit cost
TWP	Total water production
W_{eq}	Equivalent Work of thermal energy in KWh/ m^3

Publications

1. Energy consumption in seawater desalination plants in Saudi Arabia: Realities and challenges, “ world Congress on Desalination and Water Reuse” , International desalination association (IDA), Tianjin, China2013.

2. Economic evaluation of seawater desalination in Saudi Arabia, Heriot-Watt Postgraduate Research Conference, 2012, Heriot-Watt University, Edinburgh.

3. Analysis of cost of water production from seawater desalination in Saudi Arabia, “world Congress on Desalination and Water Reuse”, International desalination association (IDA), Perth, Australia 2011.

4. Seawater desalination plants in water resource provision in the Kingdom of Saudi Arabia, Saudi International Conference, 29-31 July 2010 UK, Manchester, Manchester University.

Chapter 1 - Introduction

1.1. Statement of the Problem

The bulk of the human body is made up of water, a substance we cannot live without. Plants and other animals also require water in order to survive. However, not all areas in the world have sufficient water to support life and many have a shortage of conventional fresh water. This is particularly true for the arid regions, making water scarcity one of the most serious threats to the sustenance of life in such regions, where typically the average annual rainfall is less than 200 mm (Abderrahman, 2005). In order to address this shortage, many countries have supplemented their water deficit using non-conventional water sources, the most common and acceptable being the use of desalination techniques. Other countries have also relied on the re-use of wastewater effluents for the same purpose but wastewater re-use is not socially acceptable in the Kingdom of Saudi Arabia (KSA) and its application is limited to non-potable uses e.g. groundwater recharge and irrigation but even in such applications extensive treatment to remove pathogenic organisms is routine (KAUST, 2011).

Saudi Arabia is an extremely arid country, with the range of annual rainfall being between 70 to 100 mm (Raouf, 2009; Zawad, 2008). In order to solve the problem of the shortage of drinking water (and also as a strategic measure), Saudi Arabia has embarked on large scale seawater desalination to cover the deficit in drinking water provision (Abderrahman, 2000). The first of the desalination plants was the Al-Wajh and Duba plant, set up in 1969, with a production capacity of 198 m^3 per day. Currently, Saudi Arabia is producing more than 4.9 million m^3/day of water (Pankratz, 2013), representing over 56% of total domestic water demand (Alhedar, 2013). However, this will inevitably increase in the future due to a rapid increase in demand caused by population expansion among others.

Although Saudi Arabia has been relatively successful in its strategic choice of desalination for redressing the water demand-supply deficit, the problem with this method, however, is the high cost of water from these plants. Production costs of desalinated water have recently been declining, as an outcome of improvements in the associated technologies such as the invention of the energy recovery device in the reverse osmosis membranes process (Kamal, 2008; Ettouney & Wilf, 2009). Other applications have been used to reduce the cost of desalination plant production, such as hybrid desalination or the co-generation principle for power and desalination plants (Al-Karaghouli & Kazmerski, 2013; Al-Mutaz & Al-Namlah, 2004; Buros, 2000), for example. Despite these developments, costs are still comparatively much higher than for conventional water. For example, the cost of one metric cube of water produced by a desalination plant is 0.5-8.0 US$, while for ground water, it is between 0.25 to 1.0 US$ (Al-Karaghouli & Kazmerski, 2013; Al-Zubari, 2003; Ghaffour et al., 2013), i.e. less than a fifth of desalination cost. In the past few decades, Saudi Arabia has spent a significant part of its annual budget on the seawater desalination industry, e.g. in 2013, the general budget of Saudi Arabia allocated over 33 billion Saudi Riyals (8.8 billion US dollars) for seawater desalination, which accounted for 3.85% of the total budget (Aleqtisadiah, 2014; MF, 2013).

The increasing recognition that its excessive costs will remain a deterrent to the widespread adoption of desalination, despite the huge abundance of the raw seawater source, has engaged researchers to further understand the relationship between cost and the factors that contribute to these costs. Thus, there have been a number of efforts to study and understand the relationship between these factors and the final cost of distilled water, along with developing various models to predict the cost of distilled water to improve the management and planning of the desalination industry, as will be discussed in section 2.4.6. The majority of these prediction models, however, have been developed based on the construction cost (i.e. capital cost) only and do not undertake a more detailed evaluation of the operational costs, which are a significant part of the total water cost. Besides, because these models are largely empirical, relying for their calibration on data collected from specific countries, they are unlikely to be applicable in countries with different social-economic and other situations. The cost of energy or labour and technical criteria, i.e. sea water salinity, in Saudi Arabia, for example, would be expected to be radically different from that in the USA and Western Europe; so empirical models may not be interchangeable between these areas.

As implied above, there has been no comprehensive economic study undertaken in Saudi Arabia to understand the cost effect relationship of the various factors of seawater desalination plants presented, despite the large desalination industry. The lack of this type of study has resulted in a lack of clarity for planners and decision makers in the desalination industry in Saudi Arabia. Thus, this research will attempt to study the cost of water production in desalination plants in Saudi Arabia, along with the other factors influencing the cost component.

The current study has been carried out to develop a predictive model of the cost of desalination plants in Saudi Arabia. It has been performed based on data collected from 16 seawater desalination plants in Saudi Arabia, over a period of ten years (2001 to 2010). Data from each plant include the following: capital cost; operational cost; seawater salinity; product water salinity; type of desalination technique; total water production; and energy consumption. Furthermore, in order to obtain better results and characterise the uncertainty of the predictive models, a Monte Carlo simulation approach has been used in the model development. The research methodology includes re-evaluating the capital cost with consideration of the time value of money, an estimate of the missing value of operating costs by disaggregating the annual values, and estimations of the energy consumption of each desalination plant included in the research. The final step was the development and validation of a predictive model.

1.2. Research Questions

The research will concentrate on the seawater desalination technology in Saudi Arabia. The technical factors that have affected the cost of the distilled water will be evaluated. There are three pertinent questions addressed:

(I) What are the main factors affecting the cost of production in seawater desalination plants in Saudi Arabia, and how significant is each of these?

(II) How can these factors be used to create a predictive model of the cost of fresh water produced from seawater desalination plants in Saudi Arabia?

(III) What are the uncertainties in the calibrated models and how can these uncertainties be quantified and used to improve decision making?

1.3. Aim and Objectives

The aim of this research is to identify the factors that determine the cost of water production at desalination plants in Saudi Arabia and to use these to develop a predictive model for production costs.

The objectives are to:

i. Review the water resource situation and its management in Saudi Arabia.
ii. Review different desalination techniques being applied both in Saudi Arabia and internationally, and identify the key factors that affect their production cost.
iii. Collect data (capacity, cost history, type of technology, raw water quality, etc.) on existing seawater desalination plants in Saudi Arabia.
iv. Carry out an exploratory correlation analysis with a view to identifying those factors which are statistically significant for the production cost.

v. Formulate, calibrate and validate different regression models for predicting the production cost, using the identified factors as explanatory variables.
vi. Carry out sensitivity studies on the developed models and make recommendations as to their utility for prediction.
vii. Develop a Monte Carlo simulation approach to characterise the uncertainty limits of the developed models.

1.4. Significance of Research

It is necessary to understand the relevant factors that have a significant effect on the overall cost of water produced from the seawater desalination plants in Saudi Arabia. These factors can then be used to create a predictive model of the cost of fresh water produced from these plants. Salient features of this research can be summarised in the following points: firstly, data have been collected and models have been developed based on monthly readings, which is the first of its kind in this desalination intensive nation, more accurate and practical prediction models; secondly, the desalination industry in Saudi Arabia is a public sector concern, which leads to differences in the finance cost of capital cost as (as discussed in Chapter Three); thirdly, the data are collected from desalination plants in the same country, which means that all of them have same economic criteria and thus homogenious; fourthly, all these plants are large desalination plants where their installed capacity is more than one million cubic meters per month. Finally, all these plants apply the co-generation principal, where each of them has two functions: (1) to produced distillate water and (2) to generate power from the power plant.

The research is significant because the results will be useful in assisting in technical decisions made within the desalination industry in Saudi Arabia, or any other country with same economic and technical criteria (i.e. the Gulf Cooperation Council Counties (GCC)), in order to budget effectively for current plants during the production processes, as well as at new seawater desalination projects. Whenever there is accurate information on budget cost, there will be improvement in management performance, which leads to cost reduction (Kaplan & Cooper, 1998). For example, supplying valuable cost information to the desalination plant management will avoid any delay in operation and maintenance activities due to financial problems.

1.5. Thesis Organisation

As can be seen from Figure 1-1, the current thesis contains eight chapters. Chapter One is the introduction and presents an overview of the research issues addressed in this study, including the research questions and the aim and objectives of the research. The chapter also outlines the significance of the research.

Chapter Two has been divided into four sections. Section one is an introduction to Saudi Arabia. There is firstly a discussion concerning the political and economic system, as well as geographical characteristics. The second section gives an overview of the types of water resources in Saudi Arabia and the ways in which they are managed. There is also an outline of demand and the ways in which it has been affected by population growth. The third section discusses seawater desalination systems that have been used in Saudi Arabia and gives general information about the principles of different desalination techniques that have been used in seawater desalination plants. Configurations of seawater desalination plants are also discussed in this section, alongside providing a general overview of the situation of the seawater desalination industry in Saudi Arabia. The fourth, and final, section of this chapter discusses the cost of water production from seawater desalination plants. There is an outline of the types of costs in desalination plants and factors that could affect this, based on previous studies. The final part of this section gives a summary of previous studies carried out on the predictive models of water cost from seawater desalination plants, both from within the study area and internationally.

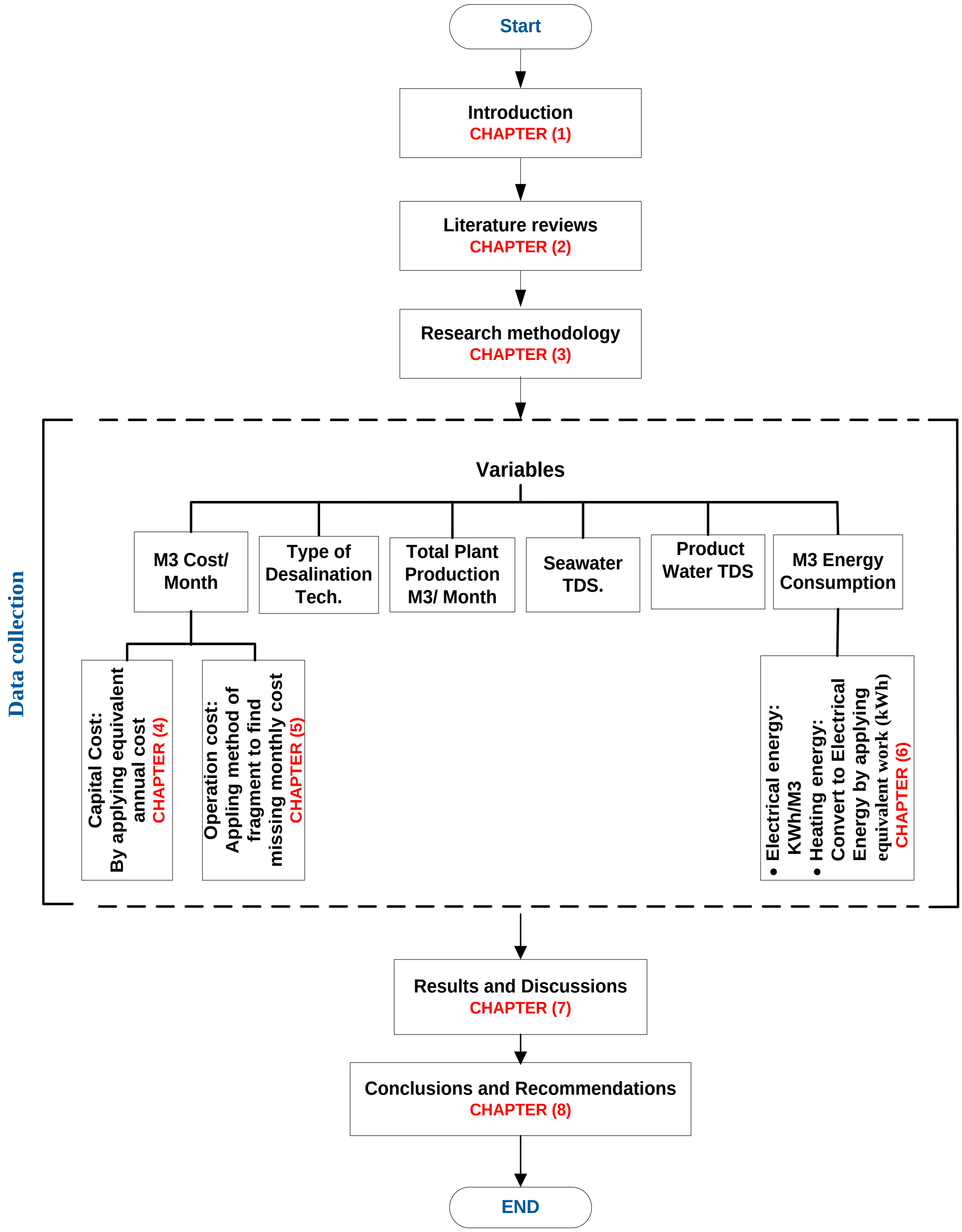

Figure 1-1: Thesis organisation

Chapter Three covers the study methodology of predictive models. The methodology includes the description of the data collection process, limitation of the data and important features of the collected data. It also comprises the description of the pre-processing of the historical data, correlation study, and development process of different regression models that have been carried out in current study.

Chapter Four describes the estimation of annual capital cost. The methodology includes characteristics of each desalination plant included in the current research. There will be a further discussion of the most effective method of estimating the annual capital cost and best rate of return value that can be used to estimate a public project, such as desalination plants in Saudi Arabia, alongside a discussion and estimation of the salvage value that can be applied.

Monthly values of operation costs are not available for some years, and so, in order to overcome this problem, these have been estimated. This issue has been resolved in Chapter Five by estimating the monthly operation costs by using the Method of Fragments. This method uses available annual operation costs, which have been divided to obtain the monthly cost. Three approaches to this have been used. The methodology contains applications of each of these approaches and compares them to identify the ideal approach for the estimation of the monthly operation cost of a desalination plant.

In Chapter Six a further issue concerning data collection has been resolved. The problem here concerns the estimation of the total energy consumption in a plant using two types of energy (electrical and heating), as used by the majority of desalination plants included in this research. The methodology in this chapter will present the estimate of consumption of both types of energy. The equivalent electrical work to heating energy consumption has been used to standardise the unit of energy consumption.

Chapter Seven presents and extensively discusses the main results of the study, including the Monte Carlo simulation experiments carried out to quantify the uncertainty limits for the prediction models.

Chapter Eight presents the final conclusion of the study. It also puts forward a number of recommendations for future research.

Appendixes are provided in CD rom and contain original collected data (Appendix A), results of method of fragments (Appendix B), results of the energy consumption (Appendix C), final data used for cost models development (Appendix D), frequency distribution comparison before and after applying the Box-Cox method (Appendix E), statistical parameters comparison between historical and generated data (Appendix F), whiskers and box plot diagrams comparison between historical and generated data (Appendix G), and Equivalent annual cost on different r values (Appendix H) .

Chapter 2 - Literature Review

2.1. Introduction

The Kingdom of Saudi Arabia is the formal name of Saudi Arabia. It is located in South Western Asia (Middle East) between latitudes 16.5-32.5^{o}N and longitudes 33.75-56.25^{o}E (see Figure 2-1). As indicated by its name, it is the kingdom established in 1932 by King Abdul-Aziz Al-Saud. Saudi Arabia is the largest country in the Arabian Peninsula, with a land area of 2,250,000 km^2 (CIA, 2013; FAO, 2008). Saudi Arabia is a new name of the Bin-Saud family state, which has governed most of the Arab Peninsula since 1744 (Al-Rasheed, 2010). The most significant features of Saudi Arabia are the two holy mosques, situated in Makkah and Madinah, to which millions of world Muslims make a pilgrimage every year, in accordance with the teachings of Prophet Mohammad. This makes Saudi Arabia to be at the heart of the Islamic world and religion.

Saudi Arabia is an arid country (FAO, 2008). With an average rainfall of less than 100 mm, it has no rivers or lakes, and the majority of its land is desert. In the summer, the average daytime temperature is 45°C, while in winter the temperature drops to under 0 °C (Hussain et al., 2010). Evaporation is therefore very high especially in the summer. The most significant terrain consists of the Rub-alkali desert (Empty Quarter) in the southeast, one of the biggest deserts in the world, and the Alsarut Mountains, located in the west of the country along Red Sea.

As seen in Figure 2-1, Saudi Arabia is divided into 13 provinces: (1) Jawf; (2) Northern Borders; (3) Tabuk; (4) Hail; (5) Madinah; (6) Qasim; (7) Makkah; (8) Riyadh; (9) Eastern Province; (10) Baha; (11) Asir; (12) Jizan ; (13) Njran. Each one has a separate governor and administration for all government services, i.e. education, health, etc. (RESAW, 2013).

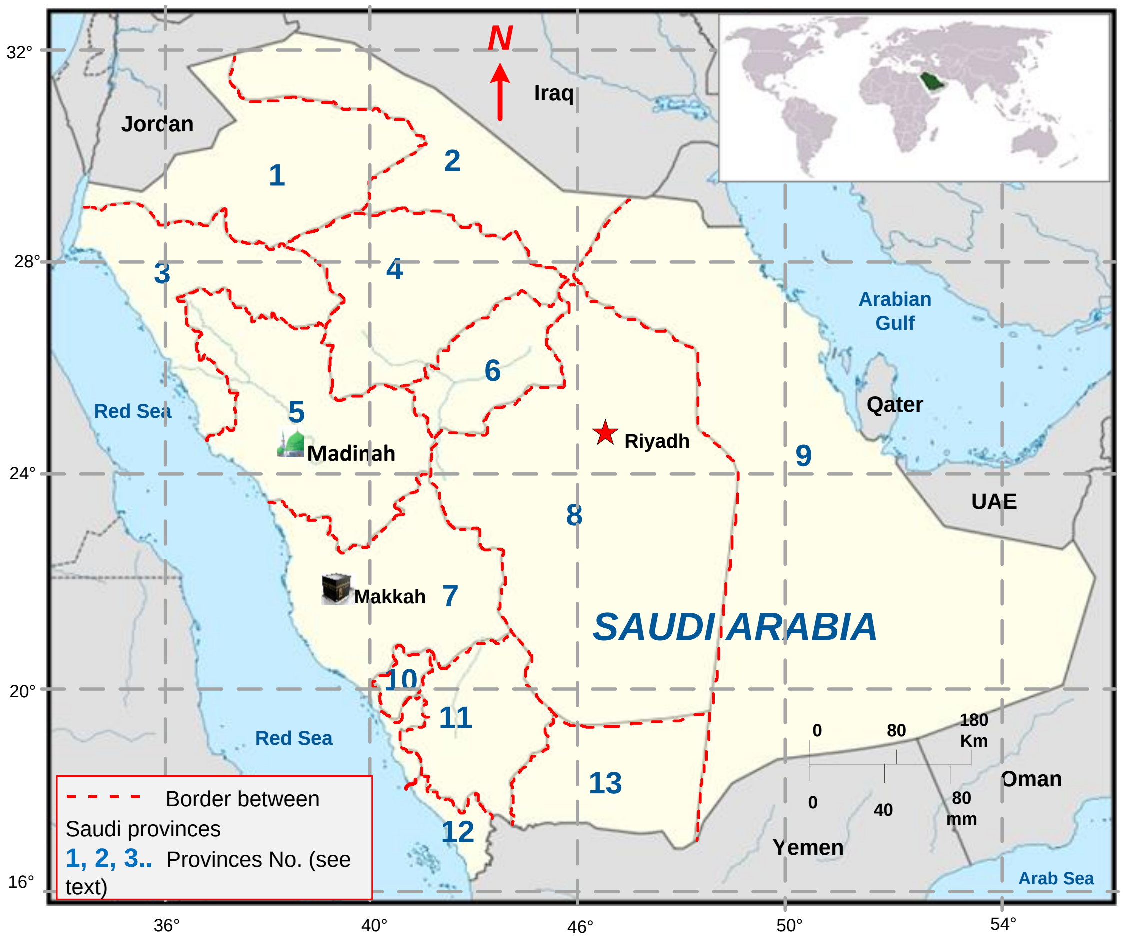

Figure 2-1: Saudi Arabia and its provinces (SUSRIS, 2013)

Saudi Arabia is a free market economy. It is a member of the World Trade Organisation (WTO) and The Group of Twenty (G20, 2013; RESAW, 2013). Saudi Arabia is the largest producer and exporter of crude oil, which accounts for 90% of total exports and 70% of national income (Chowdhury & Al-Zahrani, 2013a). Gross Domestic Product (GDP) reached $577 billion in 2013, thus making it one of the strongest mono-cultural economies in the world (TE, 2013).

2.2. Water Resources and Demand in Saudi Arabia

Water is of prime importance to the existence of life. Water resources are an important issue for any country, especially a country where there is a shortage of fresh water supplies because the average annual rainfall is very low. In Saudi Arabia, there are two types of water resources: conventional and non-conventional.

2.2.1. Conventional Water Resources

Conventional water resources in Saudi Arabia include surface and ground water. Surface water is formed from rainfall. The Ministry of Water and Electricity in Saudi Arabia has estimated the total amount of runoff in Saudi Arabia is 5 billion cubic metres (BCM) per year (MWE, 2014a). Some of this water is used to recharge the shallow aquifers, by storing it in 422 recharge dams throughout the country (MWE, 2013c). However, most of this water (90%) is lost through evaporation (Chowdhury & Al-Zahrani, 2013a; MWE, 2014a). Although the rainfall is low, it is also characterised by significant spatial variability. For example, only 12% of rainfall occurs on the Arabian shelf (which comprises two-thirds of the country as shown in Figure 2-2), (Edgell, 1992), with the remainder (88%) falling in the western coastal region known as the Arabian Shield. Thus, the majority of the landmass of Saudi Arabia has considerably limited surface water resources.

The ground water found in deep aquifers on the Arabian shelf was created 10,000 to 32,000 years ago, with the total amount estimated at 2185×10^9 m^3 (Abderrahman, 2005). It is believed that the total amount of water contained in shallow aquifers is approximately 84×10^9 m^3 (Abderrahman, 2005) . The water in the deep aquifers is non-renewable, and that in shallow aquifers is almost completely non-renewable, due to the high evaporation. The annual average consumption from the aquifers is between 11.6 to 13.5×10^9 m^3 while the annual recharge is around 1.19 x10^9 m^3 (Chowdhury & Al-Zahrani, 2013a). Most of consumption comes from the non-renewable deep aquifers leading to gradual decrease in the safe yield of these aquifers and other environmental problems such as salt water intrusion (Abderrahman, 2005; Al-Zubari, 2003).

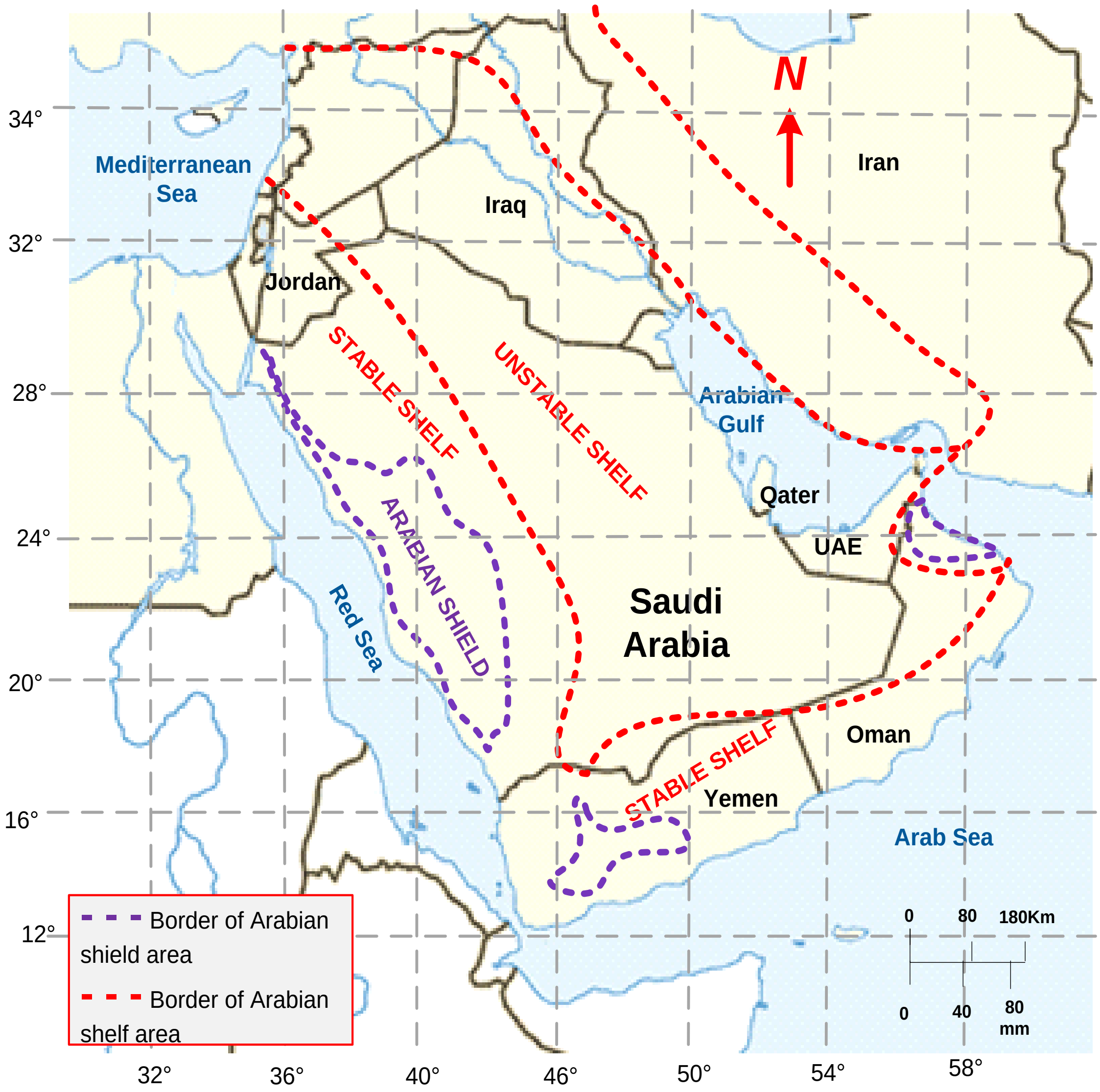

Figure 2-2: Arabian shelf (Edgell, 1992).

2.2.2. Non-conventional Water Resources

Non-conventional water resources include water from desalination plants and that from wastewater treatment plants (Abderrahman, 2000). Due to a large increase in the Saudi Arabian population, the water produced from desalination plants rose rapidly from 7.65 MCM in 1980 to more than 1055.1 MCM in 2010 (SWCC, 2011), making sea water desalination plants the largest contributor, at 56 %, of domestic potable water in Saudi Arabia (Alhedar, 2013). More details about the sea water desalination industry in Saudi Arabia are mentioned in section 2.3.2.

With respect to the treatment of wastewater, only 50% of domestic wastewater was being treated in 58 wastewater plants by the end of 2012, at a total capacity of 3,135,000 m^3/ day other households use septic tanks and soakaway pits (KAUST, 2011) which is a major concern with regard to the quality of shallow ground water in this areas. The reason for this low percentage is because of the low coverage in wastewater sewerage networks and plants (MWE, 2013b). Currently, the treatment is concentrated in major cities such as Riyadh, Jeddah, Makah, Madenah, and Dammam, while wastewater treatment in rural areas is almost unavailable. The Ministry of Water and Electricity in Saudi Arabia has a plan to reach 100% wastewater treatment for communities with a population of more than 5000 by 2025. The plan contains 41 plants under construction, at a total capacity of 2,188,000 m^3/day and 39 plants under study and in the design period at a total capacity of 1,500,000 m^3/ day (KAUST, 2011).

The current levels of treatment at wastewater plants vary from plant to plant. There are three types of treatments namely, primary, secondary and tertiary. Primary treatment has been designed to remove 50% to 60% of total suspended solids and tertiary treatment is an advanced treatment that can remove more than 99% of all impurities from sewage water by using a granular surface or membrane filtration (KAUST, 2011; WB, 2014). However, the most widely applied treatment in wastewater plants in Saudi Arabia is secondary treatment, which includes primary treatment but with additional treatment and can remove up to 85% of total suspend solids and organic materials. It is worth mentioning that the Ministry of Water and Electricity plan for wastewater in 2025 is that all waste water plants in Saudi Arabia will work on the tertiary treatment principle (MWE, 2014b).

The characteristics of the current effluent depend on the level of treatment and uses of effluent as per the Saudi wastewater regulations. For example, if the effluent is used for agricultural irrigation purposes, as in the case of most of the wastewater treatment in Riyadh city, tertiary treatment must be applied. However, if the effluent will be discharged to the sea such as at most current Jeddah and Dammam plants, only up to secondary treatment is applied (KAUST, 2011). In general, only 15% of the final effluents have been re-used in Saudi Arabia and the remainder (85%) discharges to the sea or is lost due to natural evaporation. Most of the reused effluents (60%) are used for agricultural irrigation purposes, 28% for landscape irrigation, 10% for industrial use, and 2% for aquifer recharge (Chowdhury & Al-Zahrani, 2013a; KAUST, 2011), See Figure 2-3.

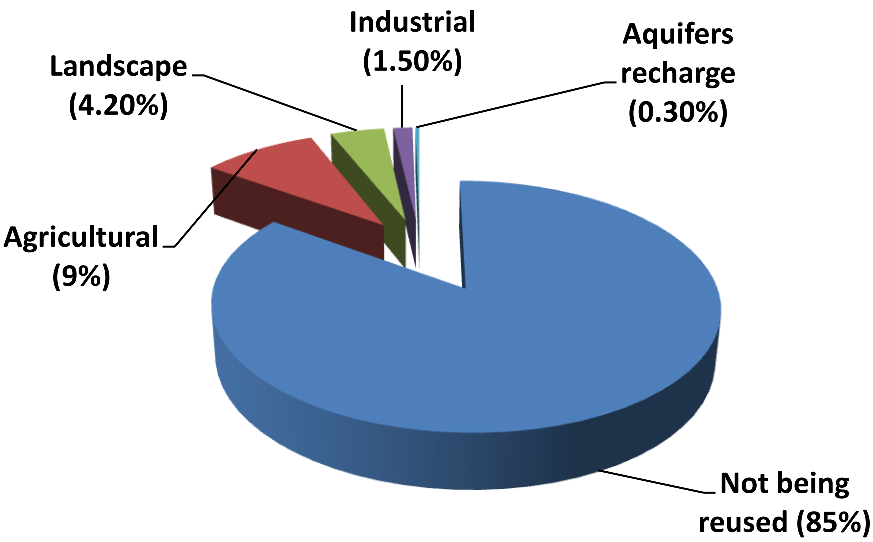

Figure 2-3: The destination of the final wastewater effluents.

In summary, wastewater treatment in Saudi Arabia is still less than might be expected in such an arid country. Even though, there is a large extension in wastewater treatment works in Saudi Arabia planned in near future, Saudi society is not accepting the reuse of effluent. To overcome this attitude, King Abdullah University of Science and Technology has suggested a wastewater education strategy. The aim of this strategy is to educate people in Saudi Arabia to understand the quality and safety in the use of effluent, especially after tertiary treatment, for different purposes such as agricultural and aquifer recharge (KAUST, 2011).

2.2.3. Water Demand

With a high average annual growth rate of 2.39%, as shown in Figure 2-4, the population in Saudi Arabia has increased rapidly from 7.7 million in 1970 to approximately 22.5 million in 2004, and is expected to reach 45 million by 2050 (MEP, 2013; UN, 2011). This considerable increase in population is due to the prevalence of large Saudi families, with an average of eight members per family (Almuneef et al., 2004). As a result, water demand has increased sharply from 2,352 x 10^6 m^3 in 1980, until it hit a peak of 31,696 x10^6 m^3 in 1992, much of it in agricultural production, after which it went down dramatically to 14,100 x10^6 m^3 in 2000 (Figure 2 -5). This decrease was due to new government regulations at the time which placed greater restrictions on private well-drilling for irrigation and reduced by 75% the financial support for wheat cultivation (Abderrahman, 2000).

One of the main objectives of the 2000 regulations was to reduce demand for water for agricultural purposes; however, water demand has risen steadily again since 2000, reaching 18,300 x10^6 m^3 at the end of 2009 (Abderrahman, 2000; Chowdhury and Al-Zahrani, 2013a). This increase was due to expansion in other crops and in livestock. For example, the production of dates, milk, and poultry meat increased from 0.734, 0.71, and 0.482 metric tons (1000 kilogram) in 2000 to 1.08, 1.67, and 0.576, respectively, in 2010 (FAOSTAT, 2014). The Saudi farmers have switched from wheat cultivation to fodder crops cultivation of which consumed 16 times more water than wheat does (CSIS, 2011). Although the agricultural water demand was 18,300 $x10^6$ m^3 in 2010 (Figure 2-5), the Saudi Arabia government has a plan to reduce the agricultural water consumption to 12,794 $x10^6$ m^3 in 2015 by reducing agricultural production and introducing advanced irrigation techniques (MEP, 2010). To cover the shortage in food security, the Saudi government started to support Saudi investment in agricultural activities abroad (EI, 2014; MEP, 2010).

In general, demand for water has increased by more than 770% from 1980 to 2010. According to the population growth forecast (Figure 2-4), it will require 6,480 $x10^6$ m^3 by 2050, if the average per capita consumption remains constant at its current level, which was 394 litres per day in 2010. The dependence on non-renewable ground water to meet total water demand (agriculture and domestic) increased from 37% in 1980 to 66% in 2001 (Abderrahman, 2005). Moreover, water quantities from desalination plants grew from 220 m^3/day in 1970 to more than 4.9 million m^3/day in 2012 (Pankratz, 2013)

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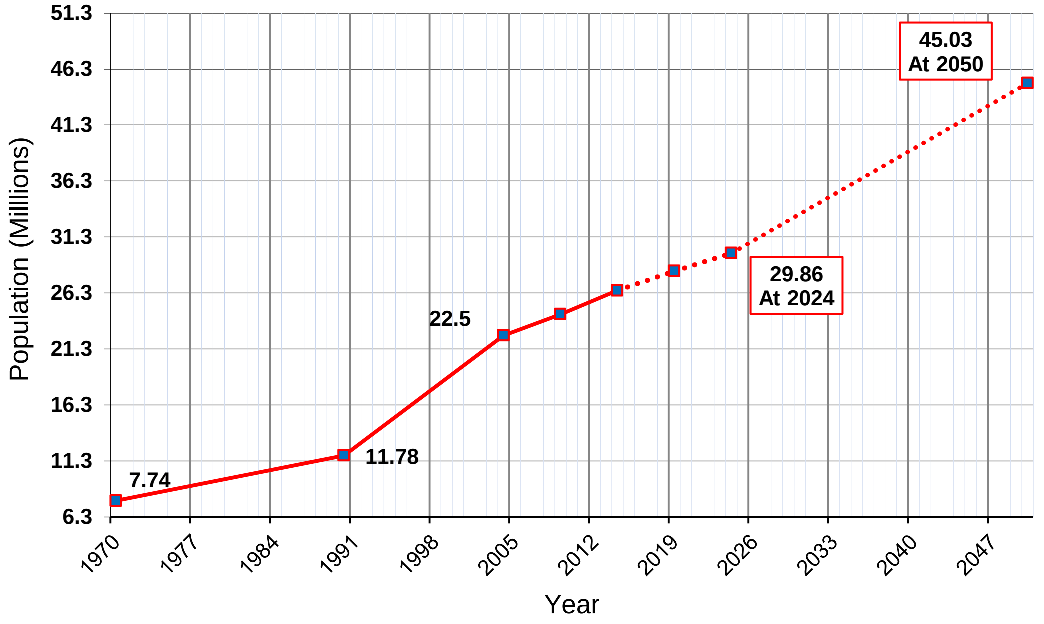

Figure 2-4: Population growth forecast in KSA (MEP, 2013; UN, 2011)

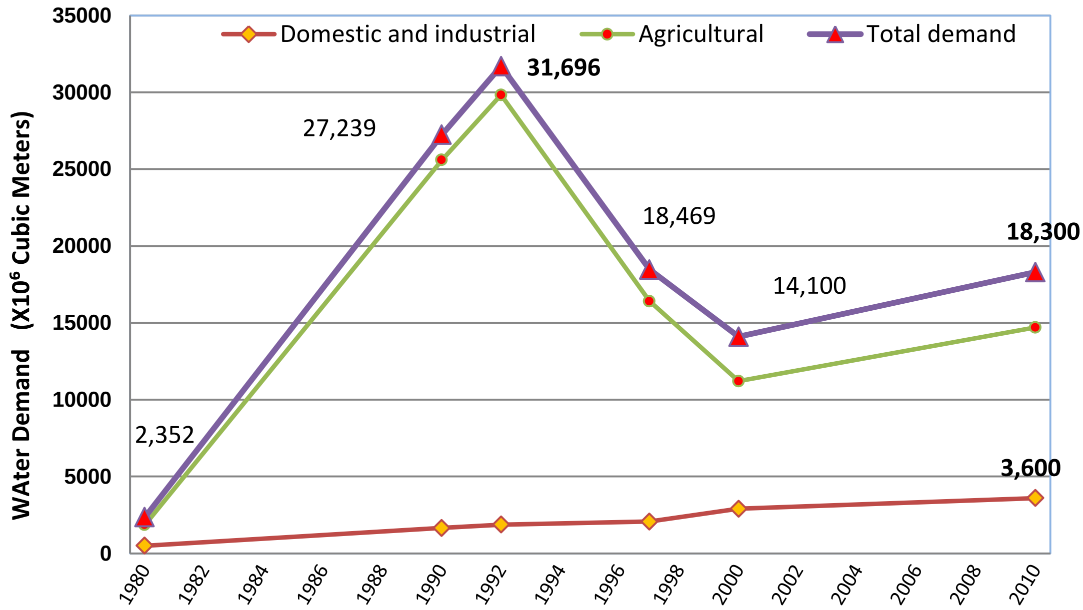

Figure 2-5: Annual Water Demand in KSA (Abderrahman, 2000).

Although some studies (e.g. Zawad, 2008) have predicted increased rainfall in Saudi Arabia over the following 70 years, of between 30% to 41%, this is unlikely to significantly alter the limited role of fresh surface water resources in Saudi Arabia. Consequently, groundwater will constitute the only viable fresh water resource but its abstraction with little or no recharge makes it vulnerable to reduced yields and pollution, such as salt water intrusion. Moreover, according to a recent study, evaporation in Saudi Arabia is expected to increase by more than 50% during the period 2011 to 2050, due to an increase in temperatures by between 1.8°C to 4.1°C (Chowdhury and Al-Zahrani, 2013b), further limiting the water available from runoff for aquifer recharge. In such a situation, an increase in temperature can seriously affectscrop yields in the country. For example, wheat production falls by between 10 to 30 percent for each 1◦C temperature increase (Alkolibi, 2002).

Consequently, desalination plant production needs to be increased to meet demand, but there is an issue concerning the high cost of water from desalination plants. As mentioned earlier, understanding this cost and factors that significantly determine it will enable operators to devise cost reducing interventions.

2.2.4. Water management institutions in Saudi Arabia

The Ministry of Water and Electricity is responsible for water resources in Saudi Arabia. The ministry's responsibilities can be categorised as in Figure 2-6. The first is a direct responsibility for water production from boreholes and wells for agriculture and domestic purposes. This includes the Vice-Ministry for Water Sector and the main central department in the ministry head office in Riyadh. The other is indirect responsibility, which includes the supervision of other organisations considered to be a part of the water management, such as the National Water Company (NWC), the Saline Water Conversion Corporation (SWCC), and The Electricity &Co-Generation Regulatory Authority (ECRA) (MWE, 2013a).

i. Vice-Ministry for Water Sector

There are three major tasks for the Water Sector of the MWE (MWE, 2013a):

- Design and contracting water and drainage projects, with a budget of more than one million Saudi Riyals.
- Giving licenses for water wells, whether for drinking purposes or for agriculture.
- Undertaking research and studies concerning water aquifers, as well as recording any change.

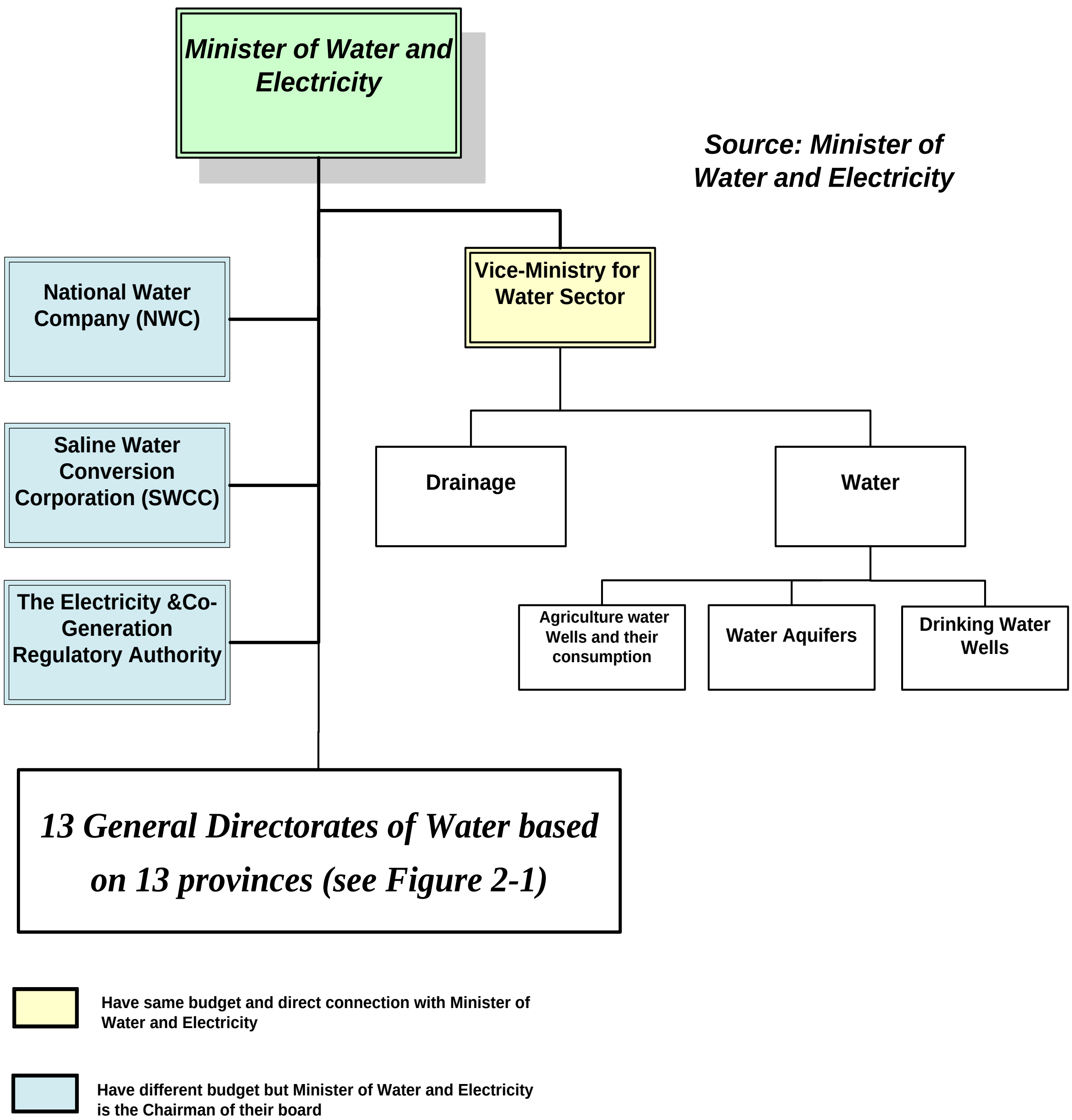

Figure 2-6: Organisational chart of water management institutions in Saudi Arabia.

ii. General Directorates of Water

As mentioned above in section 1.1, there are thirteen administrative provinces in Saudi Arabia. Each region has a separate general directorate of water, with the following powers and responsibilities (MWE, 2013a):

- To ensure the supply of drinking water for all people in their region, including city water networks, drinking water wells, and covering any shortage in desalination plant supply.
- To oversee the operation and maintenance of drainage networks and waste water treatment plants.
- To design and award contracts for water and drainage projects with budgets of one million Saudi Riyals or less.

iii. National Water Company

The National Water Company (NWC) is a joint stock company completely owned by the Saudi government and supervised by a board of directors chaired by the Minister of Water and Electricity. It was established in 2008 to provide water and wastewater services for the Saudi's cities. It currently covers only Riyadh, Jeddah, and Taif (NWC, 2013). The NWC holds the same responsibility as the general directorates of water, but also has more power, due to the fact that there are no limits for its project budgets.

iv. Saline Water Conversion Corporation

The Saline Water Conversion Corporation (SWCC) is a Saudi general corporation with its own financial and administrative independent system. It was established in 1974 to build, operate, and maintain seawater desalination plants. It is supervised by a board of directors chaired by the Minister of Water and Electricity. The SWCC has the following powers and responsibilities (SWCC, 2013a):

- To build, operate, and maintain its power and desalination plants.
- To transfer the water produced to the cities.
- To ensure the supply of drinking water according to the agreement with the relative General Directorates of Water.

- To ensure the supply of electricity according to the agreement with the Electricity Company.

v. The Electricity and Co-Generation Regulatory Authority

The Electricity and Co-Generation Regulatory Authority (ECRA) is a financially and administratively independent organisation, which regulates the electricity and water desalination industry in Saudi Arabia. It is supervised by a board of directors chaired by the Minister of Water and Electricity. The ECRA has specific responsibilities that fall into four major groupings (ECRA, 2013):

- Licensing of generation, transmission, retail, distribution and trading of electricity and cogeneration, and licenses for the production of desalinated water, along with its transportation to distribution points.
- Calendar tariffs that pay for electricity services, water desalination, cogeneration, including to periodically review these tariffs and propose amendments.
- Developing criteria and standards for the manufacture of electricity and water desalination plants, and ensuring compliance with the application and follow-up performance indicators for providers of these services, including reviews.
- Identifying the public interest for the electricity industry and water desalination, including the development of private organisations to expand this industry, and encouraging private sector participation in investment in the electricity industry and water desalination.

2.3. Sea Water Desalination

The majority of the Earth is made up of water, with 96.5 % this being in the oceans and seas, 1.7% is contained in the ice caps, glaciers, and permanent snow, and 1.03% is saline ground water, saline lakes, soil moisture, etc. Only around 0.77% is fresh water suitable for human consumption (Gleick, 1996).

Desalination refers to any treatment of water that removes salt. The idea of desalination arose in order to cover the shortages in fresh water by taking advantage of the huge amount of salt water in the oceans and seas. For centuries, there were many efforts to make fresh water from saline water but the results had little success (A-Sofi, 2001). A major step in desalination improvement came during the Second World War, in 1940, when many countries wished to supply their troops in arid areas. In the early 1960s, the USA government created the Office of Saline Water (OSW) which supported basic key research and development into desalination technologies (Buros, 2000). Nowadays the world is much more dependent on desalination plants, since the global capacity for desalted water has increased from 5.09 $x10^6$ m^3 per day in 1980 to more than 74.83 $x10^6$ m^3 per day in 2012 (Pankratz, 2013)

A great variety of methods of desalination exist worldwide, all of which produce water suitable for drinking and other municipal uses. Desalination techniques can be used for brackish water as well as for seawater.

2.3.1. Configuration of Seawater Desalination Plant

A seawater desalination plant comprises six areas (Figure 2-7): (1) seawater intake; (2) seawater treatment (pre-treatment); (3) desalination units; (4) energy supply; (5) fresh water treatment (post-treatment); and (6) brine discharge (disposal). Each one of these areas has particular characteristics, equipment and design, the differences depending on seawater properties and plant capacity (Buros, 2000).

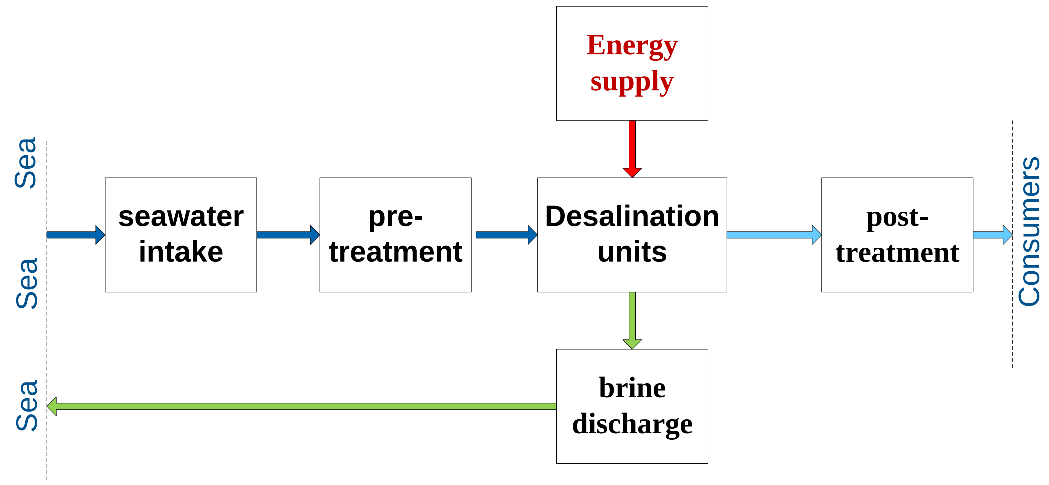

Figure 2-7: Flowchart of seawater desalination plant.

i. Desalination Units:

A large number of desalination technologies are applied commercially. There are two main categories of the main processes (Figure 2-8). The first is a thermal process, which separates the water from the salt by converting the water in seawater to vapour by heat energy and later cooling the vapour to liquid. This principle is used by the three techniques comprising multi-stage flash (MSF), multi-effect desalination (MED) and a mechanical vapour compressor (MVC). The thermal desalination process can work with a wide range of intake seawater temperatures and salinity (Ettouney & Wilf, 2009). The second is the membrane process, which operates on the difference in size between the molecules of water and molecules of salt. This is a physical process that uses either hydraulic or electrical energy to move either salt or water through a membrane to induce two zones of differing salt concentration to produce fresh water (Dore, 2005) . The main types of this process are reverse osmosis (RO), electrodialysis (ED), and nanofiltration (NF). Table 2.1 shows the world's distribution of desalination plants, from which it is clear that RO (the membrane process) dominates. The most popular thermal process is the MSF. The RO desalination installed capacity has increased from 42% (Pankratz, 2010) in 2002 to 63% currently (Pankratz,

2013) of the total installed desalination technology worldwide. The main attraction of RO desalination process is the low unit cost compared with other processes, especially in these days of high energy cost (Kim et al., 2009; Wittholz et al. , 2008; Zhou & Tol, 2005). For further details, please see section 2.4.5.

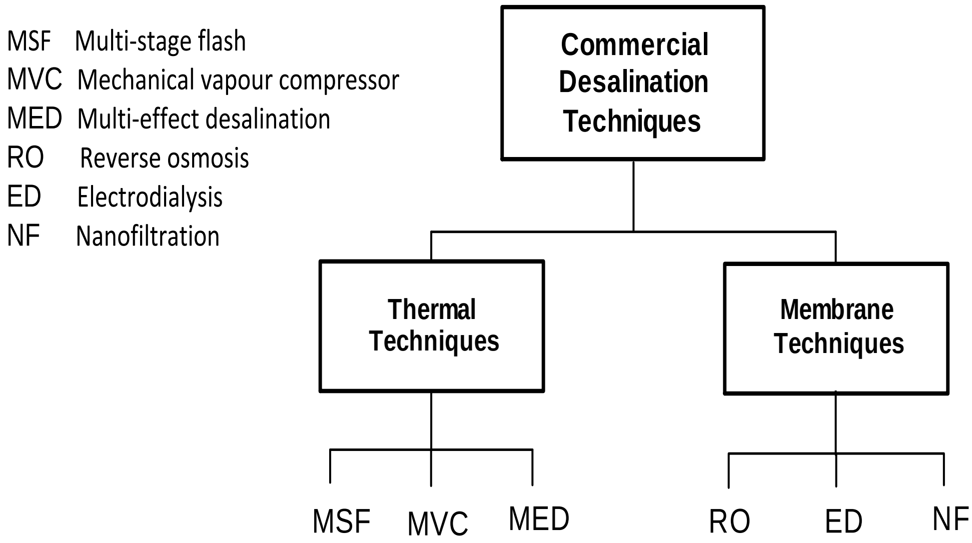

Figure 2-8: Classification of commercial desalination techniques.

Table 2-1: Installed capacity by desalination technology worldwide in 2012 (Pankratz, 2013).

Type of Technology	% of production world wide
Multi-stage Flash (MSF)	**23**
Multi-effect Distillation (MED)	**8**
Reverse Osmosis (RO)	**63**
Electrodialysis (ED)	**3**
Hybrid	**1**
Other	**2**

Additional desalination techniques can be used to produce fresh water from high salinity water, but these are not yet applied commercially due to a number of technical problems. For example, the freezing desalination technique follows the principal of separating salt from water at freezing temperatures. As a natural phenomenon in this technique, the dissolved salt in saline water is excluded during the formation of ice crystals. Then the ice will be washed to remove salt, before the crystals are melted to produce low salinity drinking water. One of the major difficulties in this technique is the handling process of the ice (Buros, 2000). Another difficulty is that the energy consumption in the freezing desalination technique is much higher compared to other desalination techniques, since one litre of fresh water produced by the freezing desalination process consumes 334 kilojoules, while in the evaporation processes, one litre requires 14-25 kilojoules of energy (Buros, 2000; WDR, 2014) The second example of desalination is solar humidification, which is a natural evaporation process by solar energy to heat the saline water in a room with a transparent roof to evaporate water then condense the vapour on the roof as shown in Figure 2-9, but this is not yet suitable for large-scale production. According to the research, the average humidification area needed to produce 10 litres per day is 2.5 m^2, which means the area needed to produce 100,000 m^3 of fresh water per day is 25 km^2: one that is difficult to manage (Buros, 2000; Shatat et al., 2013).

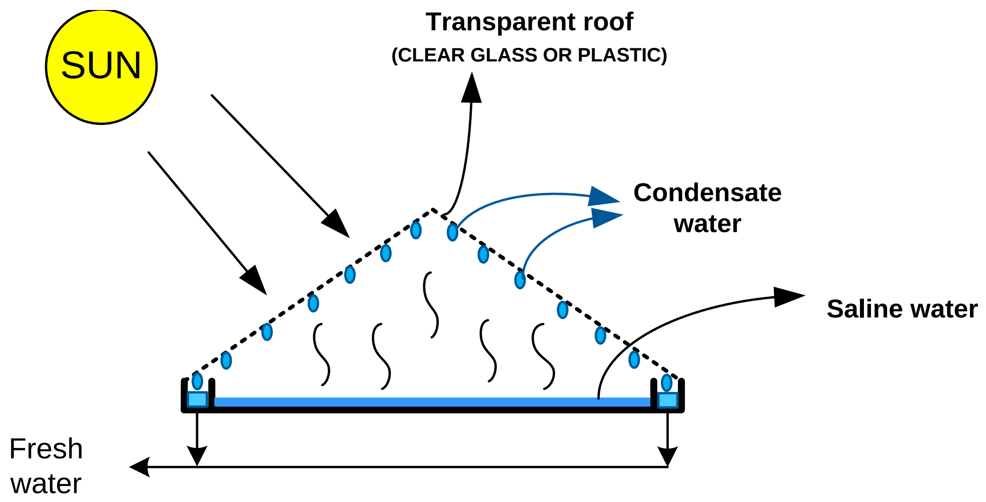

Figure 2-9: Solar humidification desalination principle.

Multi-Stage Flash (MSF)

The simple principal of multi-stage flash (MSF) is heating water to produce as much vapour as possible at low pressure and temperatures in a series of many successive stages. As shown in Figure 2-10, the hot seawater (which is the highest brine temperature *T1*) will enter the first stage and pass through other stages until it reaches the final stage at the lowest pressure *Pn* and temperature *Tn*, Figure 2-10. The pressure and temperature in each stage is lower than the in the previous one. For example, stage 2 has lower pressure and temperature than stage 1, and so on. For example, in a MSF desalination unit such as the Shuaiba-2 plant, the first stage temperature and pressure are 102.3°C and 1.1 bar respectively. The seawater passes through stage two, where temperature and pressure are 98.9°C and 0.98 bar respectively, and so on, stage by stage, until it reaches the last stage, where the temperature and pressure are 38.7°C and 0.07 bar respectively. In each stage, there is a new boiling point to generate vapour from seawater. In each stage an amount of vapour is condensed by condenser tubes above the seawater. These tubes are cooled by inlet seawater to the desalination unit from stage to stage until they reach the brine heater. As temperatures difference between the first stage seawater inlet and the final stage increase, the MSF desalination unit efficacy will increase.

It is important that the MSF technique is designed and operated at low temperatures, as far as possible, in order to avoid corrosion and scaling. At high temperatures, of which the maximum is 120°C , the chances of corrosion will be greater, alongside increased scale formation (Aly & El-fiqi, 2003; Khawaj & Wie, 2001). One of the most significant scales in MSF desalination technology is calcium sulphate ($CaSO_4$), which is hard and difficult to remove once accrued. It can be minimised by strictly controlling the high temperature between 90°C - 120°C and the salinity of seawater, and adding anti-scalant solution. Although a number of optimization studies have been carried out to reduce anti-scalant dose rates at high performance of MSF (Hamed & Al-Otaibi, 2010; Hamed et al., 2000), it has been found that anti-scalant dosing has created a marked increase in the cost of production (Al-Sahali & Ettouney, 2007).

Scale formation in the MSF desalination process is the most critical thing that causes major damage to the desalination unit. When it occurs, it will reduce the heat transfer, which leads to a decrease in the desalination unit's efficiency. It may cause the unit to have to be stopped for cleaning or to replace the condenser tube, which will cost a lot of time and money. Therefore, the temperature of the MSF desalination unit must be minimized in the design period as much as possible and a good temperature control system devised (Hawaidi & Mujtaba, 2010).

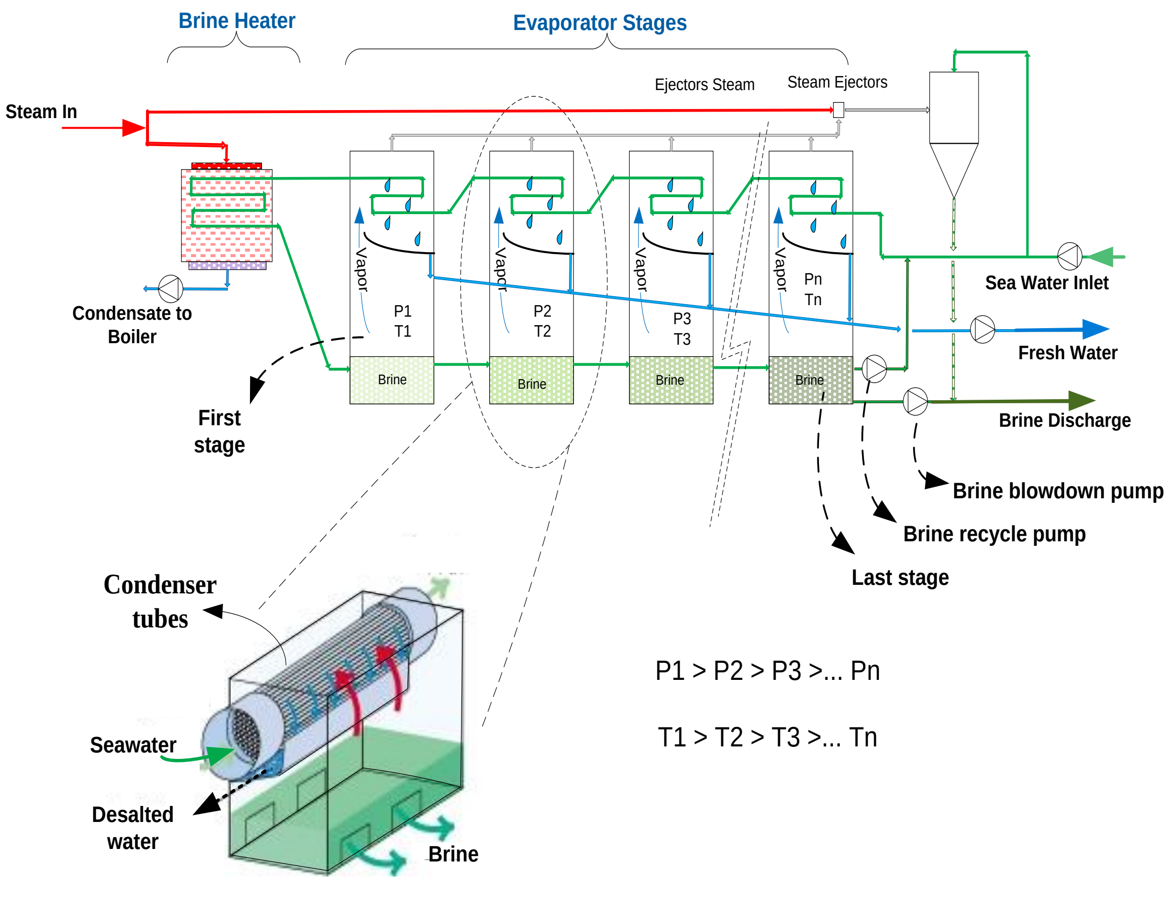

Figure 2-10: Diagram of multi-stage flash (MSF).

Multi-effect Distillation (MED)

Following the principle of reducing scaling and corrosion of thermal units, the multi-effect desalination technique (MED) has been used in desalination industries. The operating temperature in MED is below 70° C, which reduces the chance of scale building up in the desalination unit (Aly & El-fiqi, 2003). The difference between the MSF and MED is that the steam (or heated energy) in MSF is in the brine heater in the shell of the heat exchanger (see Figure 2.10), while in MED, the heated steam is in the condenser tubes (see Figure 2-11). In order to produce vapour in MED, the seawater is sprayed above the steam heat exchanger tubes. The vapour then converts to fresh water after a condensation process (Buros, 2000).

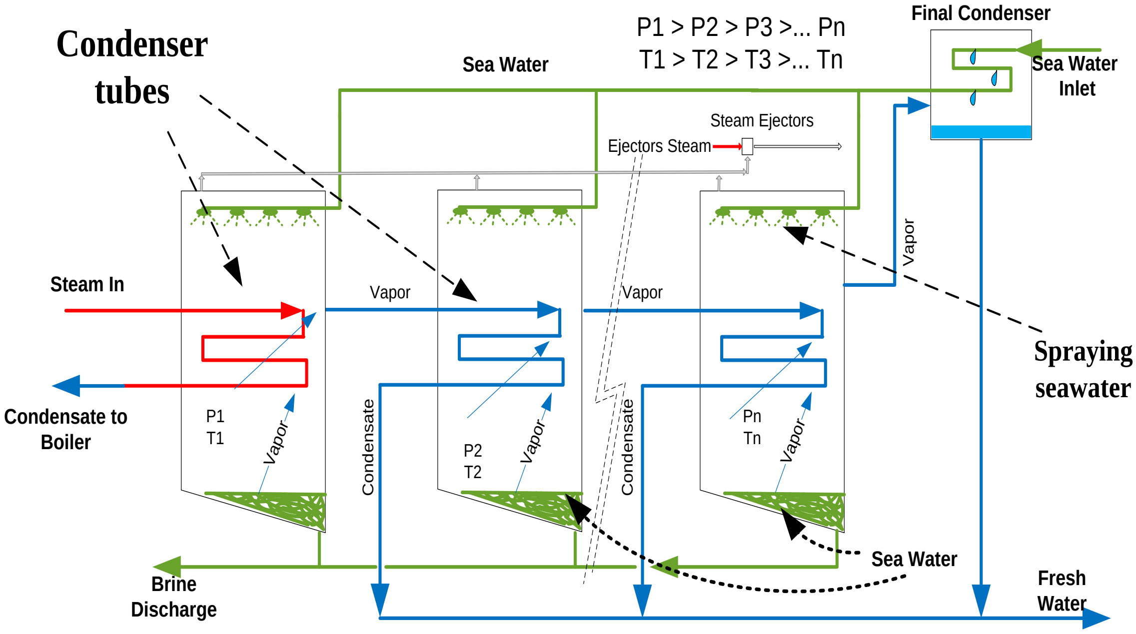

Figure 2-11: Diagram of multi-effect distillation

Mechanical Vapour Compressor (MVC)

The mechanical vapour compressor desalination technique (MVC) works based on a principle that the temperature will increase by increasing pressure. The heat for evaporating the seawater in MVC is obtained from the compressing process. The compressor pressurises the vapour inside the condenser tubes, which leads to the exchange of heat from the vapour to the spraying seawater This heat transfer results in condensing the compressed vapour in the condenser tubes (fresh water) and thus generates new vapour, and so on (see Figure 2-12).

MVC is usually applied combined with MED or for a small seawater desalination unit. Actually, one of the most important techniques used mainly with MED to increase production efficiency is vapour compression distillation (VCD). This compresses the vapour produced from the last stage of MED and uses it as inlet vapour in the first stage at the same MED. By increasing the pressure of the vapour, the temperature also increases. The power used to run the VCD compressor is generally an electrical or diesel engine (Buros, 2000).

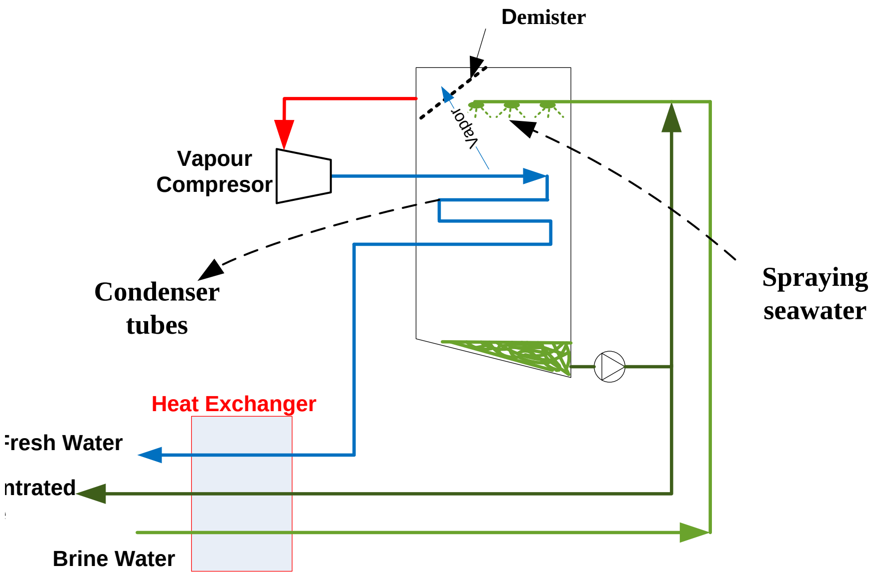

Figure 2-12: Diagram of mechanical vapour compressor.

Reverse Osmosis (RO)

When a porous membrane separates high and low salinity water, the natural osmotic movement of the water molecules will be from low salinity water to high salinity water through the membrane. In the reverse osmosis technique, the molecules of water are moved from high to low salinity water by using high pressure (Figure 2-13).

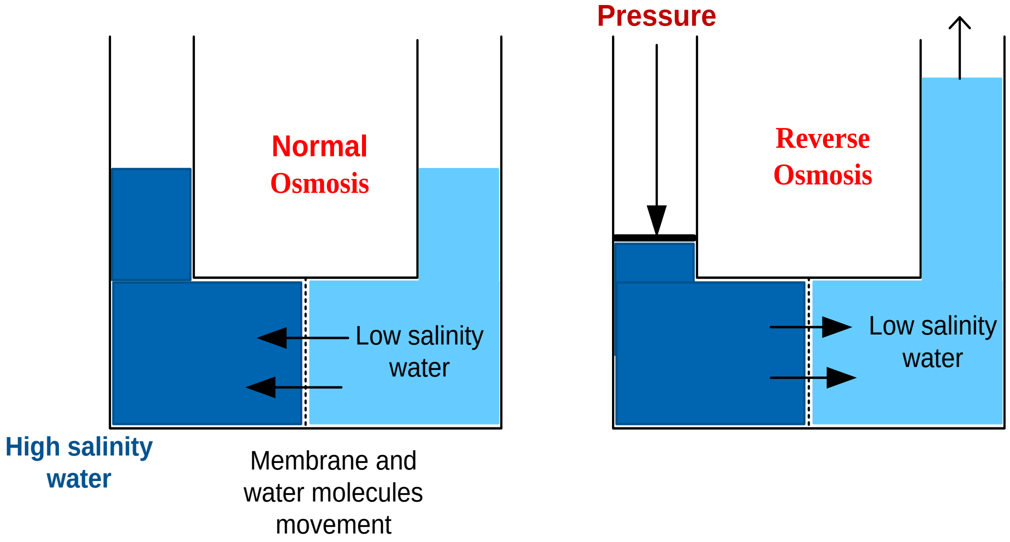

Figure 2-13: Water molecule movement in the phenomena of osmosis and reverse osmosis.

The efficiency of production in an RO desalination plant depends on the salt concentration of the inlet water, type of membrane, and the pressure applied. For example the pressure required for brackish water, where concentration of total dissolved solids (TDS) falls between 1500 ppm and 10000 ppm (Greenlee, Lawler, Freeman, Marrot, & Moulin, 2009) pressure is between 15 to 25 bar, while in seawater, where TDS is higher than 10000 ppm, pressure is between 54 to 80 bar (Buros, 2000). The pressure is provided by a centrifugal pump, as shown in Figure (2-14). This different seawater pressure leads to a significant difference in energy costs, as well as reducing the capital cost of the desalination plant.

In order to reduce energy consumption, an energy recovery device (ERD) has been invented. ERD is a pressure exchanger from a high pressure fluid stream to a low pressure fluid stream (Stover, 2004). This is one of the most important improvements in RO desalination technology. The ERD consists of mechanical equipment, generally involving turbines or pumps. It uses the high salinity outlet water pressure to rotate the ERD, which rotates on the ERD seawater side and increases the seawater pressure, thus reducing the energy power that required for inlet pressure to the reverse osmosis element (Figure 2-14). By using ERD, the energy consumption can be reduced by between 30-46% (Kamal, 2008; Ettouney & Wilf, 2009).

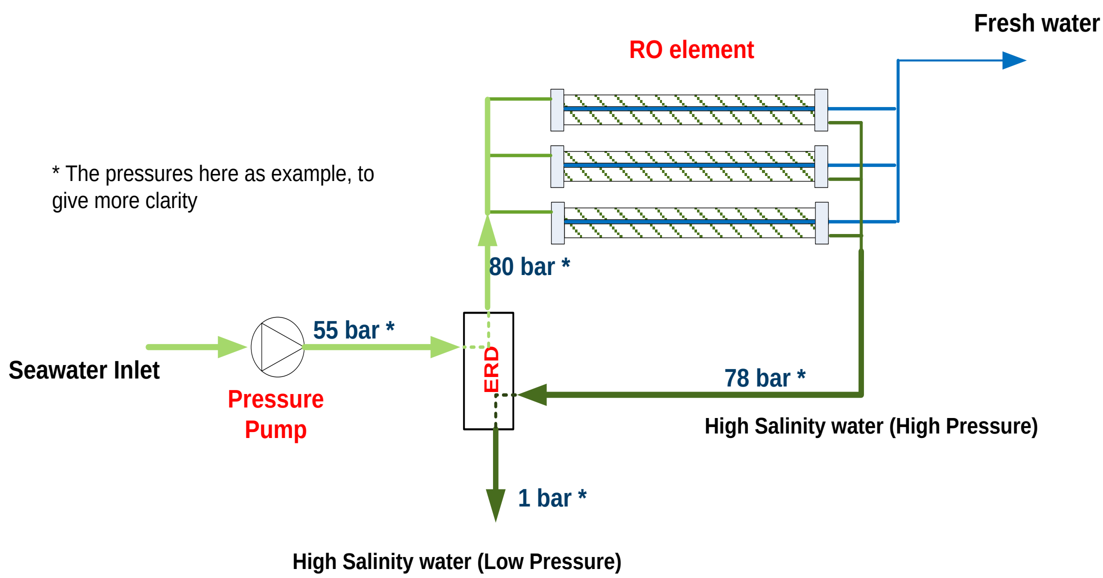

Figure 2-14: Configuration of SWRO unit with ERD

Electrodialysis (ED)

The majority of the salts dissolved in water are as ions, either cations (+) (such as sodium) or anions (-) (such as chlorine). Depending on this chemical principle, electrodialysis (ED) desalination techniques use electrical power to absorb the salt ions from the high salinity water through membranes used to separate the fresh from saline water (Figure 2-15). In ED, the driving force is the electrical force used to move the salt particle through the membrane, while the RO, the driving force, is the pressure force to move fresh water through the membrane (Figure 2-16) It is notable that the ED technique is suitable for brackish water but not for seawater, due to its high salinity (Buros, 2000; Khan A.H., 1986).

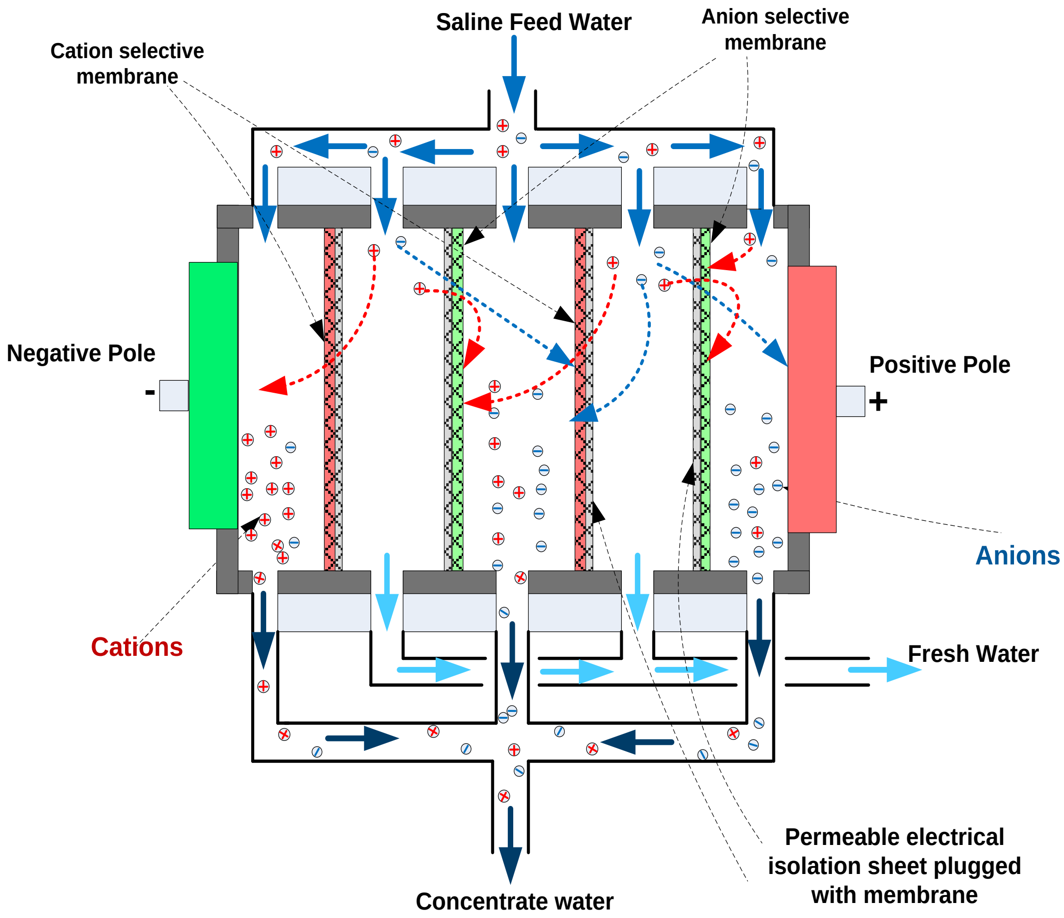

Figure 2-15: Electrodialysis work mechanism (Buros, 2000)

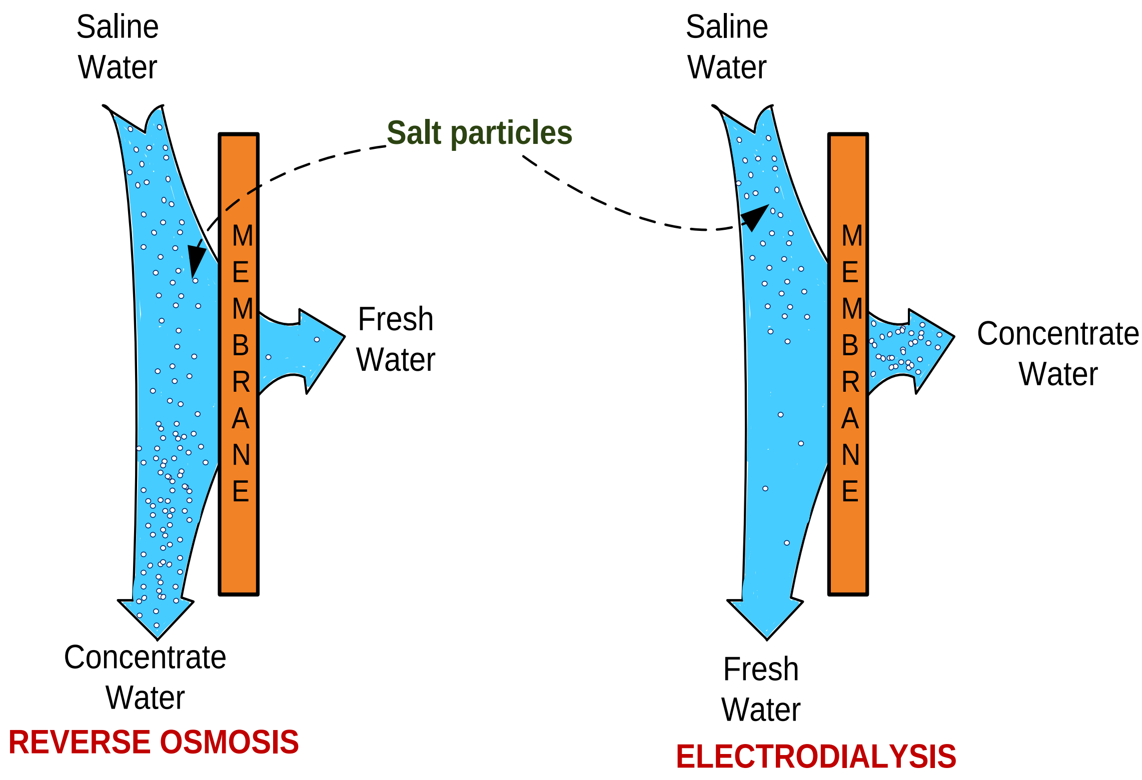

Figure 2-16: Difference in separation of salts between Electrodialysis membrane, and Reverse Osmosis membrane (Buros, 2000)

Nanofiltration (NF)

Nanofiltration (NF) membranes work on the same principle as RO. The main difference between RO and NF is the size of the dissolved solids that can be removed, with the RO removing smaller sizes than NF (SDWF, 2013) . NF membranes have been used successfully to distil brackish water with total dissolved solids (TDS) of less than 10,000 ppm (Ettouney & Wilf, 2009). On the other hand, when coupled with other desalination techniques (such as RO or MSF) they can be used as a part of a pre-treatment process to increase efficiency. NF membranes can be used to remove the hardness of ions of divalent salts like magnesium sulphate ($MgSO_4$), calcium carbonate ($CaCO_3$), or calcium sulphate ($CaSO_4$), which are responsible for the main type of scale in thermal desalination processes (Al-Ahmad & Aleem, 1993; O. a. Hamed, 2005). In addition, they can be used for many purposes to clarify and purify water, such as removing dissolved organic materials (Ettouney & Wilf, 2009; Lomax, 2009). In general, the pressure applied is in direct proportion to the salinity of the raw water in the desalination process, (Table 2-2); in the NF process it is significantly lower than in the RO process, leading to lower power consumption (Lomax, 2009).

Table 2-2: Reverse osmosis: desalination membrane inlet salinity, pressure required, and energy consumption (Ettouney & Wilf, 2009; Harussiet al., 2009; Sommariva, 2010)

Reverse osmosis membrane	Membrane inlet water TDS (ppm)	Membrane inlet pressure (bar)	Energy consumption (KWh/m³)
Nanofiltration	Less than 3,500	7-10	0.5
RO Brackish	Less than 10,000	10-20	0.8
RO Sea water (Mediterranean)	35,000	60-70	3.5
RO Sea water (Arabian Gulf)	38,000-45,000	75-85	4.5

ii. Seawater Intake:

A seawater desalination plant requires an intake system able to provide both good quality and sufficient quantity of seawater required for either the desalination process or the plant cooling system. The system of seawater intake usually includes: an intake channel (either open or closed); screening for large objects; screening for small objects; a chlorine dosing system (seawater disinfection system) which keeps the intake structure and desalination unit clean of marine growth; and intake pumps. An appropriate seawater intake design is a precondition for making production cost efficient and environmentally acceptable (Azis et al., 2000). For example, the distance between the intake area and desalination units affects the selection of seawater intake pumps, since a longer distance results in a bigger pump (higher capital costs) and higher pressure, which requires more power consumption (higher operation costs).

iii. Seawater Pre-Treatment:

The pre-treatment process is applied in order to protect the desalination units through improving the quality of seawater. This depends largely on the type of desalination technology that has been selected. Scale formation in the thermal desalination unit, due to high operation temperatures, is potentially extremely dangerous, in particular in the MSF technique. Inhibiting this scale formation is the main purpose of pre-treatment in thermal units. Three methods have been applied to inhibit the scale in an MSF desalination unit, i.e. acid treatment methods, chemical additives, or the hybrid (acid and chemical) treatment method (Hamed and Al-Otaibi, 2010). In addition, two chemicals, an antifoam and a corrosion inhibitor are added to the inlet seawater make-up of thermal desalination units. Antifoam is used to reduce foaming during the evaporation process, in order to avoid salt contamination in the product water, while a corrosion inhibitor reduces the dissolved oxygen, an important element in the corrosion process (DLR, 2007).

Membrane fouling due to slime growth can significantly reduce the performance of membrane units, and this is the focus of pre-treatment in such units. The pre-treatment process chosen is one of the most important decisions for owners of membrane-type desalination plants. In fact it is not uncommon, recently, for the selection of the membrane to be based on the pre-treatment process (Wolf et al., 2005). For a successful operational process, the pre-treatment system should be well designed, in order to reach its objectives of reducing the silt density index (SDI) for seawater to less than three, and the turbidity to less than 0.25 NTU (Prihasto et al., 2009). This is to prevent the membranes from scale formation, and to protect them from slime growth (Baig et al., 1998; Prihasto et al., 2009). If the pre-treatment does not achieve these goals, membrane fouling might result after a short period of time. This would cause a number of problems, including higher operational costs (due to higher energy consumption), increased time involved in cleaning membranes and the reduced life of membrane elements (Pontié et al., 2005).

Pre-treatment processes in membranes desalination plant are currently divided into two categories: conventional, and non-conventional. Conventional includes coagulation and flocculation, and the gravity filtration processes. The non-conventional also includes micro filtration, ultra filtration, and beach well systems (Prihasto et al., 2009). Each one of these processes has special characteristics and operational methods, leading to improved performance.

iv. Energy Supply:

Removing salt from high-salinity water requires driving force energy and therefore the desalination process uses alternative forms of energy. Three forms are used in the salt separation mechanism, these being: (1) mechanical energy as a mechanical pressure (such as the one that applies in reverse osmosis (RO) or the vapour compression desalination process); (2) thermal energy (that applies in MSF or MED desalination techniques); (3) electrical energy (such as the ED technique). Levels of energy consumption in deferent desalination techniques are included in Table 2-3.

v. Brine Discharge (Disposal):

The disposal of the residual brine of a desalination process is a major environmental issue in the desalination industry. This is because some of its characteristics e.g. high temperature, altered pH, and high salinity may affect the receiving system environment. However, each one of these can be avoided or their effect tempered by good design of the brine discharge channel and mechanism, such as providing cooling systems to reduce the brine disposal temperature or adequate control and chemical neutralising processes for the disposal of brine (Alameddine & El-Fadel, 2007; Lomax, 2009). The high salinity is not an issue in the seawater desalination processes, since the eventual disposal of the brine does not add any additional salt to the sea, resulting in no change in the amount of salt, similar to the effect of natural evaporation on sea water salinity. On the other hand, it might cause a considerable problem when it comes to the brackish desalination process, where brine disposal is one of the main environmental and cost issues that must be considered in plant operation (Greenlee et al., 2009). Environmental monitoring studies have found variable effects ranging from no significant impacts to benthic communities, through to widespread alterations to community structure in seagrasses, coral reefs and soft-sediment ecosystems when discharges are released to poorly flushed environments. In most other cases environmental effects appear to be limited to within 10 s of metres of outfalls (Roberts et al., 2010).

Table 2-3: driving forces for salt separation in different desalination techniques (Al-Karaghouli & Kazmerski, 2013; Buros, 2000; Micale et al., 2009; Pilat, 2001; Sommariva, 2010)

Desalination technique	**Desalination driving force**	**Range of energy consumption,** **(KWh/m³)***
Reverse osmosis (RO)	Pressure force	3.5-8
Electrodialysis (ED)	Electrical potential force	2.5-20
Multi stage flash distillation (MSF)	Latent heat force	19.5-27.2
Multi effect desalination (MED)	Latent heat force	12.2-19.1

*** based on water salinity**

iv. **Post-Treatment:**

The hardness or salt in water produced from a desalination plant is nearly removed. This shortage in salt is not acceptable to most health regulations, and also causes corrosion problems in the distribution network (Ettouney & Wilf, 2009; Micale et al., 2009; Nadaa et al, 1987). Consequently, once fresh water has been produced, post-treatment is vital in order to confirm and correct the water quality before sending it to consumers (Ettouney & Wilf, 2009).

The required post-treatment depends on the type of desalination technique, the end consumer, and amount of production. In a thermal desalination plant, the produced water usually has very low salinity (TDS between 10-20 ppm), which means it is suitable for industrial use, i.e. in boilers for steam production. Due to the salinity of produced water of 200-500 ppm in a membrane desalination plant, it is not suited to a number of industrial applications. Moreover, it is not suitable for domestic use, due to the removal of bivalent ions (salt) such as calcium and magnesium, which renders it corrosive and unhealthy.

In general, the PH value and hardness of water products prepared for domestic application, needs to be corrected, and a disinfection process with good residual control is the most important treatment, as it is linked directly to safe usage (Micale et al., 2009).

2.3.2. Seawater Desalination in Saudi Arabia

Saudi Arabia is the world's leader in the production of desalinated water from seawater desalination plants followed by the United Arab Emirates, Spain and the United States of America (Pankratz, 2011). The sea water desalination industry in Saudi Arabia provides fresh water from 30 operational plants at 16 locations (Figure 2-18), producing over 4.9 million m^3/day of water – close to 18% of the world's desalinated water production (Pankratz, 2013). Moreover, many more desalination projects are being constructed with large capacities, more than 1,000,000 m^3/ day (see Table 2-4).

The three desalination technologies have been applied commercially in seawater desalination plants in Saudi Arabia are MSF, MED, and RO. Of these, MSF is the most common, accounting for over 70% of the total desalination water production (Figure 2-17).

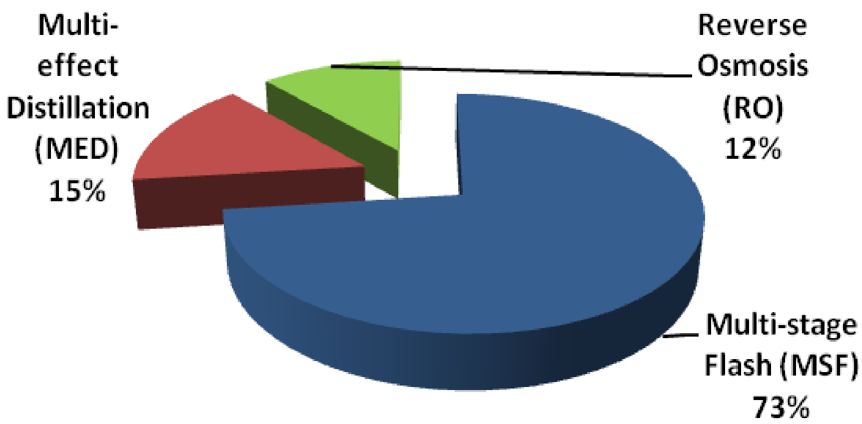

Figure 2-17: Installed capacity by desalination technology in Saudi Arabian seawater desalination plants (Pankratz, 2009, SWCC, 2010).

Figure 2-18: Seawater Desalination Plant Location in KSA.

Table 2-4: Seawater Desalination Plants in Saudi Arabia (ACWA, 2013; SWCC, 2013b).

Coast	Location	Plant	Water Capacity (m^3/ Day)	Distribution of product water to cities
West Coast	HAQL	II	3,784	HAQL
	DUBA	III	3,784	DUBA
	ALWAJH	II	946	ALWAJH
		TRANS. 1	1,238	
		TRANS. 2	619	
		TRANS. 3	413	
	UMLUJ	II	3,784	UMLUJ
	RABIGH	I	1,204	RABIGH
		TRANS. 1	774	
		R.Arabian Water	134,000	
	ALAZIZIA	I	3,870	JEDDAH
	ALBIRK	I	1,952	ALBIRK
	FARASAN	I	430	FARASAN
		TRANS. 1	1,075	
	JEDDAH	III	88,357	JEDDAH
		IV	221,575	
		R.O.1	56,800	
		R.O.2	56,800	
		R.O.3	240,000	
	YANBU	I	108,074	YANBU, ALMADENAH
		II	144,000	
		R.O.2	128,182	
		III	400,000	
	SHUAIBA	I	223,000	SHUAIBA, MAKAH, TAIF, ALBAHA
		II	454,540	
		IV	1,030,000	
	SHUQAIQ	I	97,014	SHUQIQ, JEZAN, ABHA, ALKAHMIS, ALNAMAS
		II	212,000	
	West Coast Total		3,618,215	
East Coast	KHAFJI	II	19,682	KHAFJI
	KHOBAR	II	223,000	KHOBAR, DAMAMM, ALHASA
		III	280,000	
	JUBAIL	I	137,729	JUBAIL, RIYADH, ALQASIM
		II	247,890	
		R.O.	90,909	
		Marafiq	800,000	
	RAS Al-KAIR	I	1,000,000*	RIYADH, ALHAFAR
	East Coast Total		2,799,210	
KSA Total by end of 2015			6,417,425	

*planned to come on stream by the end of 2015

2.4. Cost of Water Production from Seawater Desalination Plants

The total costs of water produced from desalination plants include capital and operation costs (Frioui & Oumeddour, 2008; Fryer, 2010; Huehmer, Gomez, Curl, Moore, & Huehmer, 2011; Khayet, 2013; Kim et al., 2009a; Waston, Morin, & Henthorne, 2003; Younos, 2005). These are described in the following sub-sections.

2.4.1. Capital Cost

The capital cost of a desalination plant includes costs that have been expended during the construction period and before the commercial use of the plant (Frioui & Oumeddour, 2008). As can be seen from Figure (2-19), the capital cost is categorised into direct capital costs and indirect capital costs (Ettouney et al., 2002; Hilton, 2005; Younos, 2005). Direct capital costs include cost of an asset that will be used later in the plant's commercial operation period (such as land, equipment, buildings, etc.). Indirect costs include any other expenditure related to the plant construction process (such as freight and insurance, field supervision, construction equipment, etc.).

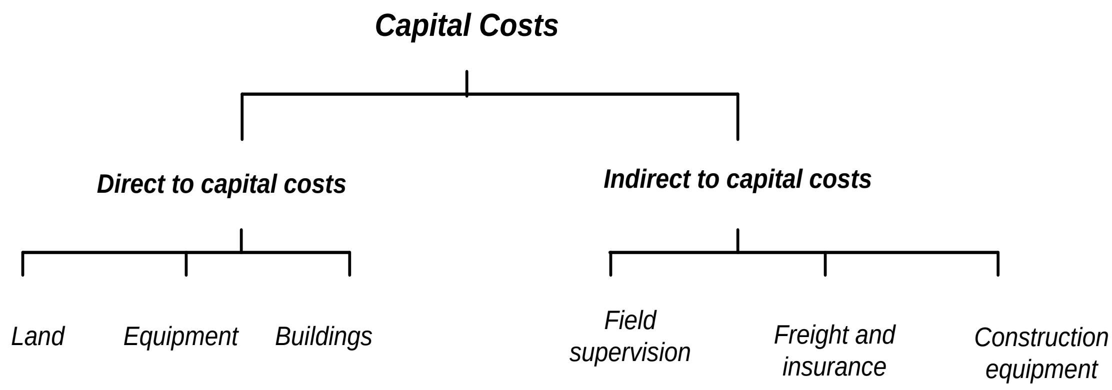

Figure 2-19: Categories of capital costs

There are two finance methods used in Saudi Arabia to estimate annual capital cost. Firstly, there is the Islamic finance method, which is simply a division of the initial capital cost by the life cycle period of each desalination plant without any interest rates (El-gamal, 2006; Usmani, 2002). For instance, if the capital cost of a desalination plant is US$100x$10^6$ and the life cycle of the plant is 10 years, then the annual capital cost will be is US$10x$10^6$. The Islamic finance method is the method generally applied to include capital costs in the total production cost of desalination plants in Saudi Arabia. The other method, which will be used in the current study, is the life cycle costing (LCC) that takes account of the time value of money, by including a rate of return of capital costs to total production cost. There are a number of different approaches to evaluate capital budget projects economically, as well as to recognise the life cycle cost (LCC). These include: payback period; discount payback; net present value; internal rate of return or equivalent annual cost (Brigham & Ehrhardt, 2005; DLMC, 2007; Fuller & Petersen, 1996; Kishk, Al-Hajj, & Pollock, 2003; Schade, 2007).

Payback Period

The payback period (BP) is the expected number of years required in recovering the capital cost of investment without considering the time value of money. The original investment is recovered by the inlet cash flow to that investment (Brigham & Ehrhardt, 2005). For example, suppose there is an investment project. The capital cost of this project is $10,000 and the life cycle of this project is 4 years. The estimated net cash flow incomes will be $5000, $4000, $3000, and $1000 at the end of first, second, third, and fourth year respectively as illustrated in Figure 2-20. In the payback period, capital cost is estimated based on the total income of each year of the project life cycle. In the current example, 50% of the total cost ($5000) is allocated in the first year, while the project will recover the original investment (payback) at 2.33 years. The project that has the shortest payback period will be selected as the preferred project (Brigham & Ehrhardt, 2005).

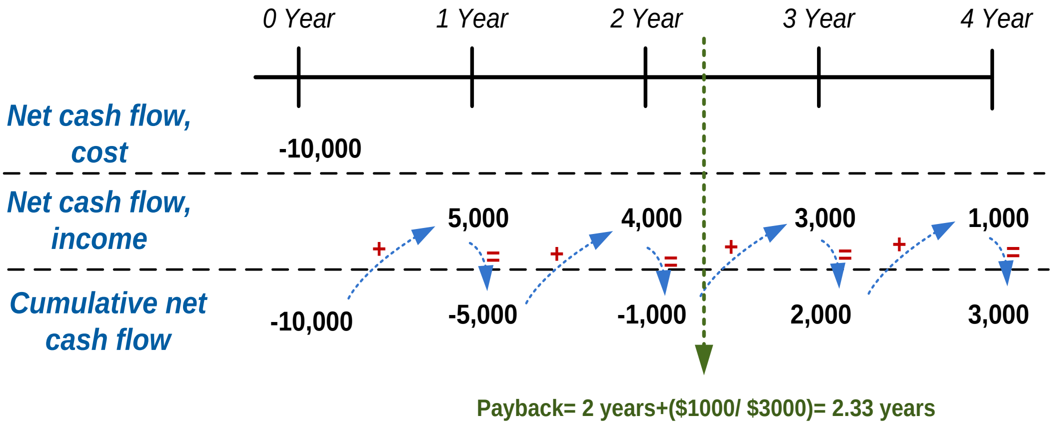

Figure 2-20: Payback period mechanism.

Discount Payback Period

The discount payback period (DPB) is the expected numbers of years required to recover the capital cost of investment with consideration of the time value of money (Brigham & Ehrhardt, 2005). As an example, if we use the same project above at 10 % discount rate, which is the interest rate used in a discounted cash flow analysis to determine the present value of future cash flows (CDC, 2013; Kishk et al., 2003), the cost of each year will be calculated as in Equation 2-1. The annual capital cost is estimated based on the discount of the total income of each year of project life cycle. In the current example, the capital cost is recovered at 2.95 years, which is the discounted payback period (see Figure 2-21). The project that has the shorter discounted payback period will be selected as the preferred project (Brigham & Ehrhardt, 2005).

$$DNCF_t = \frac{CF}{(1+r)^t} \tag{2-1}$$

where t is the year, r is discount rate, CF is year cash flow, and $DNCF_t$ is the discount net cash flow for year t.

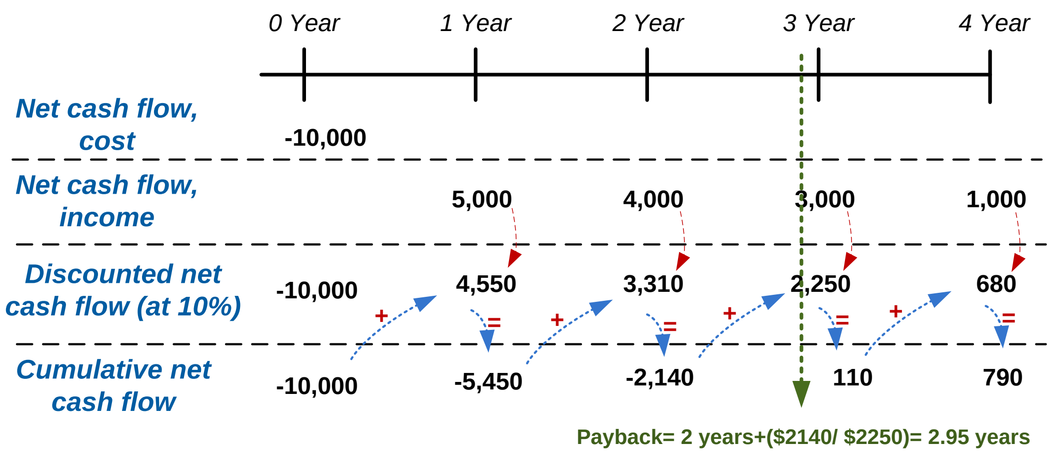

Figure 2-21: Discounted payback period mechanism

Net Present Value

Net present value (NPV) is the present value of expected future cash flows from a project, or investment, which will be based on a required rate of return. Therefore the expected future cash flows are included in the cost and profit, which will be discounted to the value existing in the first year of the investment life cycle (Schade, 2007). Using the previous example, the net present value, as calculated using Equation 2-2, will be $788.2, Figure 2-22. The project that has higher net present value will be selected as the preferred project (Brigham & Ehrhardt, 2005).

$$NPV = -CF_0 + \frac{CF_1}{(1+r)^1} + \frac{CF_2}{(1+r)^2} + \frac{CF_3}{(1+r)^3} + \frac{CF_4}{(1+r)^4} \qquad (2\text{-}2)$$

where CF_0 is the capital investment cost, and CF_1 ,CF_2, are the inlet cash flow in the project life cycle, *r* is the discount rate or rate of return (CDC, 2013; Kishk et al., 2003).

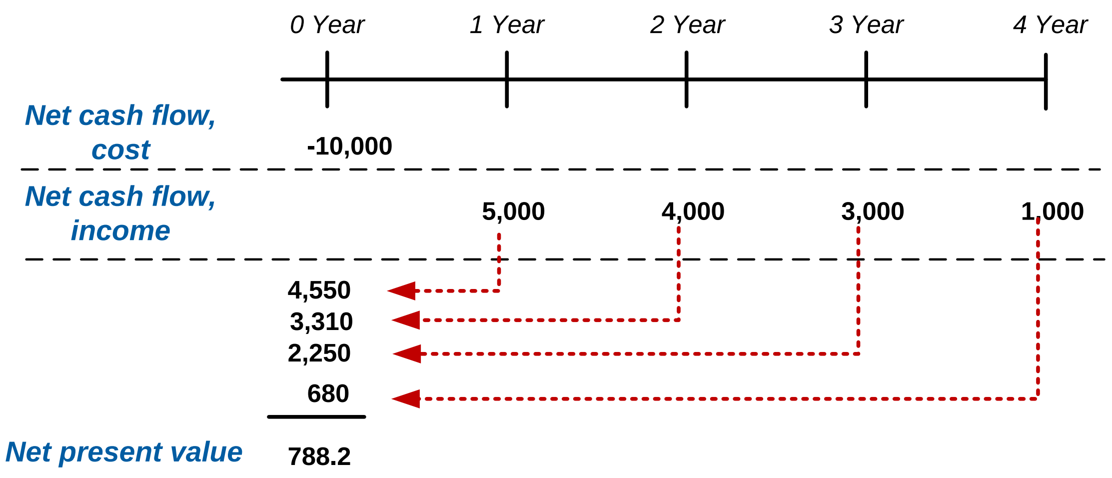

Figure 2-22: Net present value mechanism**.**

Internal Rate of Return

The internal rate of return (IRR) is the rate of return of the expected future cash inflow at the value existing at the first year of the project life cycle in certain numbers of years. It is used to compare different projects. The project that has the higher IRR is the better one to be implemented (Brigham & Ehrhardt, 2005). For instance, using same example above, the IRR is the discount rate that makes the net present value (NPV) equal to zero (see Figure 2-23). i.e.:

$$NPV = 0 = -CF_0 + \frac{CF_1}{(1+I)^1} + \frac{CF_2}{(1+I)^2} + \frac{CF_3}{(1+I)^3} + \frac{CF_4}{(1+I)^4} \qquad (2\text{-}3)$$

where I is internal rate of return. The determination of I is thus a trial and error process.

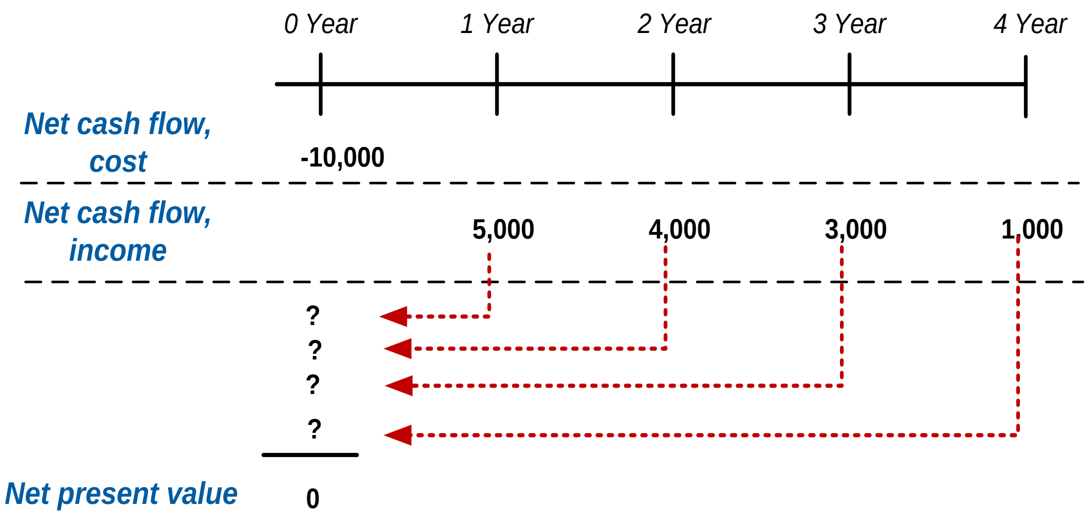

Figure 2-23: Internal rate of return mechanism

Equivalent Annual Cost

Equivalent annual cost (EAC is a financial evaluation method that can be used to calculate the average annual capital cost of any project plus the actual operation and maintenance cost of each year of the project life cycle, separately. It is related to the net current value by the annuity factor. It is also called 'amortised annual capital cost' (Zhou & Tol, 2005). The EAC evaluates the NPV of the costs and salvage value during the first year of the project's life cycle, based on the expected total life cycle of the project, Equations 2-4 and 2-5 (DLMC, 2007; Kishk at al., 2003).

$$EAC = \frac{NPV}{A} \tag{2-4}$$

where

$$\text{NPV} = \text{-CF}_0 + \text{Present value of Salvage (PSV)} \tag{2-5}$$

and

$$A = \frac{1}{r} - \frac{1}{r(1+r)^n} = \frac{(1+r)^n - 1}{r(1+r)^n} \tag{2-6}$$

Where CF_0 is the capital investment cost, A is amortization or annuity factor (Zhou & Tol, 2005). Using Equation 2-6 in Equation 2-4 gives

$$EAC = NPV * \left(\frac{r(1+r)^n}{(1+r)^n - 1}\right) \tag{2-7}$$

The calculation of the equivalent annual cost of a project with a capital cost of \$10,000, 4 year life cycle, r value at 10 % and salvage value of \$1000 is 683 is illustrated in Figure 2-24.

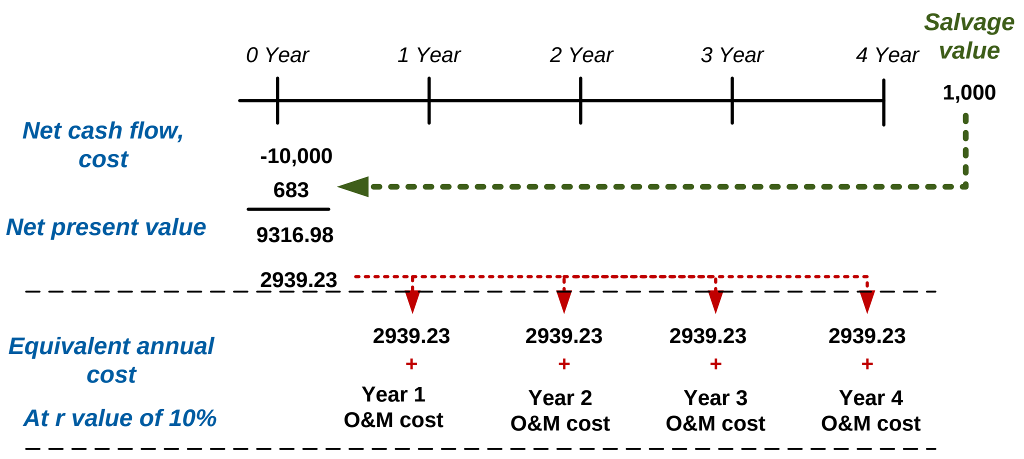

Figure 2-24: Equivalent annual cost mechanism.

2.4.2. Operational Cost

Operational cost is the cost expended after the construction period and during the plant's life cycle, and consists of repeated costs as shown in Figure (2-25). It includes direct and overhead costs (Ettouney et al., 2002; Hilton, 2005; Younos, 2005). Direct cost include the costs that are spent in operational processes, which include the fuel used to produce steam, electricity used to run operating equipment, salary of operation and maintenance staff, chemicals, such as anti-scale and corrosion inhibitors, and spare parts of production equipment. On the other hand the overhead costs include any money expended in the desalination plant but not directly intervening in the operation process. It includes utilities expenses such as security, stores, and information technology (IT). The overhead costs also include plant administration, insurance, utility such as security or fire department and general expenses such as transportation and/ or any indirect material.

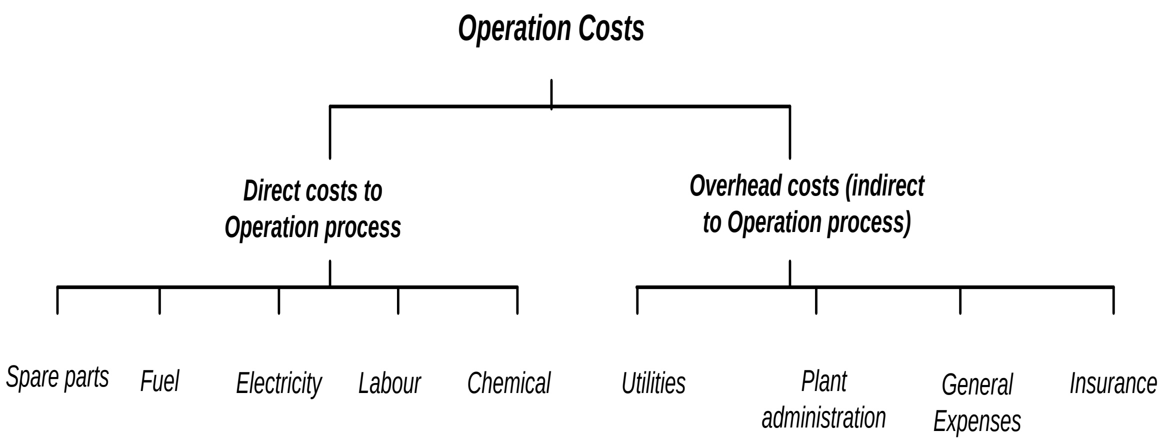

Figure 2-25: Categories of operation costs

2.4.3. Total Cost

This is the summation of operating cost and capital cost in particular periods. It is evaluated by the total unit cost, as shown in the following equation:

$$Total\ unit\ cost = \frac{TC}{Q} \quad (2\text{-}8)$$

Where

TC = total production cost in a time period

Q = total water produced in the time period

As noted before

$$TC = C + O \tag{2-9}$$

Where, C is the capital costs and O is the operational cost.

2.4.4. Interest Rate

One of the most important issues in the economic evaluation over a period of time is an account of the time value of money or rate of return. The evaluation of time of money assumes that money has been used in another opportunity, which is usually banking investment. Two aspects affect the time value of money, these being inflation and interest rates. Inflation is defined as a decline in the purchasing power of money over a time period, while the interest rate is the rate of return of investment banking across a time period (Hagedorn, 2008; Hilton, 2005).

Inflation and interest rates are different from country to country, based on the economic situation and policy. For example, in Saudi Arabia, as shown in Figure 2-26 there was negative inflation in 1986 at (-3.1)%. It rose steeply to 4.5% in 1991 then to (-0.3) % in 1992. After 2001, inflation increased steadily to 0.7% in 2005 and then jumped to 9.9% in 2008. In contrast, the interest rate was at 14% in 1982 and decreased steadily to 0.96% in 2011(Hasan & Alogeel, 2008; SAMA, 2008, 2011). In general, the interest rate in Saudi Arabia is almost matching with the interest rate in United States as it can be seen in Figure 2-27 (Bank, 2014; US Inflation, 2014).

Causes of rising and falling inflation are based on two mixed factors. The first one is the availability of money in a country's financial system. For example, increased money availability, when there is increase of wages, or government decides to print a lot of money, or there is an expansion of banks to lend money (credit) for private investment. All of these push the inflation up and vice versa: when there is less availability of money, this tends to push the inflation down (deflation). The second factor that causes a rise and fall of inflation is the supply and demand of the goods and services. When the supply of goods or services goes down, this leads the price of that good or service to go up and inflation also goes up. Agricultural products are an example of this; if there is less supply of an agricultural product for any reason, this leads to an increase in the demand of this product, which leads to increases in price (Brigham & Ehrhardt, 2005; Feldstein, 2013; Haberler, 1960).

In terms of causes of rising and falling interest rates, there are three combined factors which affect the interest rates. The first one is the inflation rate: if the inflation rate is high, the commercial banks will increase the interest rates on credit, to cover the loan's maturity payment, otherwise the loan's maturity becomes less valuable. The second factor is the supply and demand of the credits. If there is more supply for credits there will be a fall in interest rates. On the other hand, if there is more demand for credits from banks' customers, the interest rates will increase. The third factor, which is the most important factor, is the government central bank interest rate and monetary policy. The central bank of any country makes announcements about the interest rates, to control inflation and stimulate economic growth (Heakal, 2013; JMC, 2013).

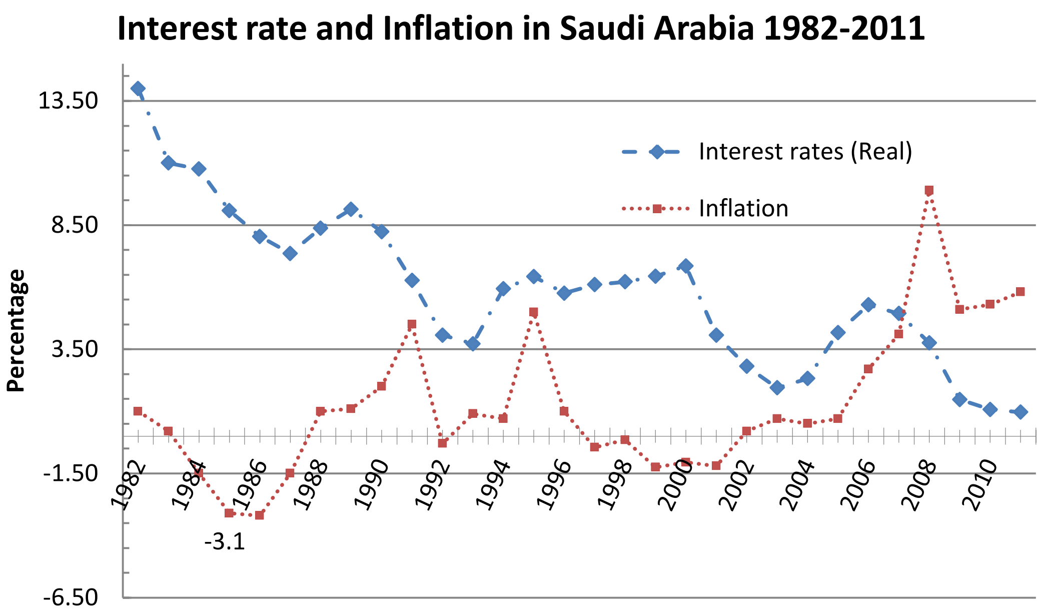

Figure 2-26: Interest rates and inflation in Saudi Arabia 1982-2011 (Hasan & Alogeel, 2008; SAMA, 2008, 2011).

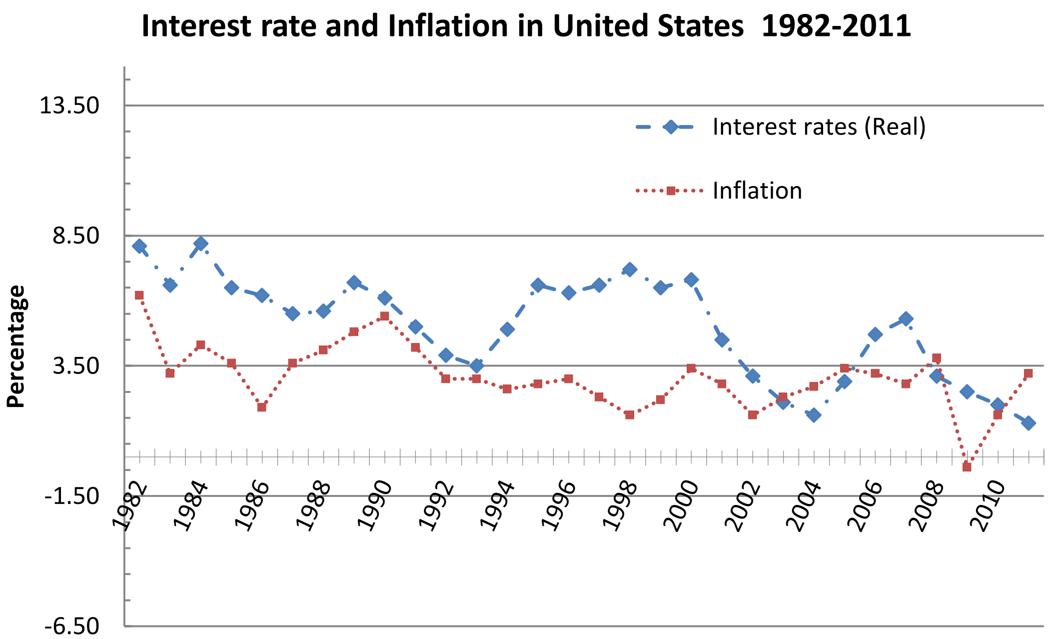

Figure 2-27: Interest rates and inflation in United States 1982-2011 (Bank, 2014; US Inflation, 2014)

2.4.5. Factors Affecting the Cost of the Production from Desalination Plants

At the beginning of the desalination industry, in the nineteen sixties and seventies, costs were high. Production costs of desalinated water have since declined as an outcome of technical improvements (Ettouney et al., 2002; Karagiannis & Soldatos, 2008), such as the invention of the energy recovery device (ERD) in the reverse osmosis (RO) plant, as mentioned in section 2.3.1 or the use of carbon steel plates instead of copper nickel plates in construction of the multistage flash desalination plant (MSF). For an example of cost history, a cubic meter of distilled water from an MSF desalination plant in 1970 varied between US$6-7/ m^3, but the international cost is now between US$0.52/ m^3-1.75 / m^3 . For SWRO, the international cost of a cubic meter of distilled water was between US$ 2.5-3.0/m^3 in 1975 but has now dropped to between $ 0.5-1.5/ m^3. It is worth mentioning that the big gap between these costs is related to the different in plants' capacity and differences in energy costs from one country to another (Al-Karaghouli & Kazmerski, 2013; Ghaffouret al., 2013; Zhou & Tol, 2005).

Various factors affect the cost of production of a desalination plant, the most important being plant total water production, feed water quality, energy consumption and cost, as well as type of desalination technique (Dore, 2005; Karagiannis & Soldatos, 2008). Other factors that may increase or decrease the cost include plant location and space requirements; manpower qualification and cost; plant life and reliability; operation and maintenance aspects; financing and disposal (Al-Sahali & Ettouney, 2007; Al-Subaie, 2007; Buros, 2000; Ettouney & Wilf, 2009; Karagiannis & Soldatos, 2008; Khawaji et al., 2008). Moreover, there are further methods used to reduce the cost of the desalination plant production, such as hybrid desalination or the co-generation principle (A-sofi et al., 2000; Al-Mutaz & Al-Namlah, 2004; Buros, 2000; Hamed, 2005), which will be discussed at the end of current section.

Plant Total Water Production

As in most industrial processes, desalination production costs are inversely proportional to production capacity (Avlonitis, 2002). Some expenses in the desalination plant are practically identical, regardless of the size of the plant, i.e. the administration cost or a large part of the labour costs. Consequently, desalination plant capacities have increased dramatically to meet the water demand, as well as to reduce the production cost (Pankratz, 2013).

Feed water quality

The quality and salinity of the inlet seawater to the desalination plant are major effects that have to be considered during the selection process of desalination techniques. Salinity of feed water is one of the most important factors in the selection of desalination technology. In terms of operation cost, the pressure on the RO desalination element to obtain satisfactory fresh water recovery is directly proportional to the salinity, which leads to greater energy consumption for seawater desalination ($TDS > 10000$ ppm) than for brackish water desalination ($1500 \text{ ppm} < TDS < 10000$ ppm) (Buros, 2000; Farooque et al., 2008; Greenlee et al., 2009).

The salinity (as well as other chemical contents) of brackish water and seawater also depend on regional location. For example, the Baltic Sea's average TDS is around 10,000 ppm, while in the Arabian Gulf the average salinity is about 48,000 ppm (A-sofi, 2001; Greenlee et al., 2009; Micale et al., 2009). The high salinity of the Arabian Gulf has forced Arabian Gulf countries to apply thermal desalination processes, despite their higher production costs (Greenlee et al., 2009). Moreover, the quality of the feed water plays a major part in membrane pre-treatment design (Baig et al., 1998; Prihasto et al., 2009; Wolf et al., 2005).

Energy Consumption

The consumption of energy is dependent on the types of desalination techniques and other activities, such as pre-treatment processes. For example, one metric cube of fresh water consumes between 15-18 (kWh), if MSF desalination is used, while it will consume 5.7-15 kWh if MED is applied (Al-Sahali & Ettouney, 2007; Ettouney & Wilf, 2009). In relation to RO, currently, one m^3 of product water consumes from 2 to 3.5 kWh/ m^3. In old plants, in the eighties in the USA, this was 6 to 8 kWh/ m^3. Furthermore, there is a target by desalination researchers and planners to reduce consumption to 1.5-2.0 kWh/ m^3 (Lomax, 2009). The main reason for this level of improvement in RO energy consumption is due to the application of energy recovery devices (ERD), as shown in Figure 2-14 (Kamal, 2008). Although RO desalination has less energy consumption, the thermal MSF and MED systems perform with higher reliability, particularly with high salinity seawater like that in the Arabian Gulf (Al-Sahali & Ettouney, 2007; Greenlee et al., 2009). On the other hand, the energy costs differ from country to country: for example, they are less in GCC countries than others, due to the fact that GCC countries are oil-exporting.

On the other hand, renewable energy can be applied as an alternative in the desalination process, but it is still considerably more expensive compared with other energy sources (Helal et al., 2008; Khawaji et al., 2008). Nuclear energy can be used, either directly to produce steam for thermal desalination plants, or through electrical energy for membranes desalination plants. However, safety considerations need to be explored that are acceptable to the community (Kavvadias & Khamis, 2010).

Type of Desalination Technique

The type of desalination technique used will affect the production cost, mainly operational costs, since the energy consumption is different between one technique and another, as previously outlined (Al-Karaghouli & Kazmerski, 2013; Ettouney et al., 2002).

Plant Location

The location of the plant will have a bearing on the production costs, particularly as in some countries labour costs and land prices are lower than in others. Moreover, shipment costs differ from location to location. A number of studies have identified plant location as having a minor impact on total production cost (Ettouney et al., 2002; Wittholz et al, 2008).

Plant Availability and Lifetime

The life of a desalination plant and its availability for continuous production are variable and depend on the material selected. Good quality plant materials will be reflected in the life of the plant, as well as its availability, and vice versa (Blank et al., 2007; Ettouney et al., 2002).

Manpower

The skill and knowledge of engineers, operators and plant management staff has a significant impact on continuous production in any industry. A good plan for operation and maintenance schedules makes a significant impact on continuous production, reducing production cost. This is true in the desalination industries, in which the availability of qualified manpower plays an important role in quality as well as availability of plant production (Ettouney et al., 2002). On the other hand, the cost of labour is one of the major operational costs in desalination plants (Ettouney et al., 2002; Younos, 2005).

Financing

The majority of investment projects, such as desalination, are financed by banks who give loans to investors. These loans have interest rates which will be included in the annual capital cost and total production cost (Blank et al., 2007; Ghaffour et al., 2013). The high interest rates will result in high production costs. For example, suppose there is an investment project. The capital cost of this project is $10,000 and the life cycle of this project is 4 years. The calculation of the equivalent annual cost of a project at 5% and 10 % interest rate will be $2820.1 and $3154.4 respectively, see section 2.4.1.

Disposal Treatment

In a brackish desalination plant, disposal treatment is one of the major costs affecting total cost. On the other hand, disposal treatment in a seawater plant is considerably less compared with other costs, as mentioned in section 2.3.1 part V (Alameddine & El-Fadel, 2007; Lomax, 2009).

Hybrid Desalination Plant

A successful method to reduce the overall costs of a desalination product is hybrid desalination, which combines two desalination techniques in the same plant (Buros, 2000). In Saudi Arabia, a number of plants in operation (such as Shuaiba-3) have depended on hybrid desalination principles for a long period of time. The desalination techniques in these plants are integrated in parallel, which means they share the intake and post-treatment of the product (ACWA, 2013). There is a proposal to take up full integration, which is integrated in a hybrid desalination plant such as NF with MSF, NF with SWRO, or MSF with SWRO, in order to avoid scaling and fouling problems, as well as increasing the MSF or RO production within the same process (O. a. Hamed, 2005).

The hybrid desalination principle consists of two objectives: the first is the reduction of the production cost by reducing scaling/fouling problems in maintenance costs, and energy consumption, which is one of the features of the RO desalination process. Second is the improvement of the production quality of the sea water reverse osmosis (SWRO) plant by blending it with MSF/MED production to reduce the TDS in the total water production of the plant (Al-sofi et al., 2000; Buros, 2000).

Co-generation

A power and desalination co-generation plant uses the same energy source for two products, water and electricity; hence it is known also as a dual purpose plant. Saudi Arabia, along with other GCC countries, have applied this principle to a large number of plants, which can run desalination units alongside a power plant, i.e. the outlet steam from the power source is used as heat energy in thermal desalination units (MSF/ MED). Although, one of the benefits of this type of plant is to reduce the capital cost investment by sharing the plant facilities, such as seawater intake and auxiliary systems, the major benefit of this integration is to reduce the energy costs, which would be higher if there was a separate power and thermal desalination plant at the same level of power and water production (Al-Karaghouli & Kazmerski, 2013; Al-Mutaz & Al-Namlah, 2004; Buros, 2000). For example, the average cost of one cubic meter of desalted water in 2009 from the Shuqiq co-generation plant was US$ 0.8/ m^3 while it was US$ 1.71/ m^3 in the Rabigh desalination plant (SWCC, 2010).

2.4.6. Predictive Model of Water Cost from Seawater Desalination Plants: Some Examples

Capital cost estimates

Much effort has been made concerning the modelling of the cost of desalination. Waston et al. (2003) provided cost curves that express the linear relationship between construction cost and plant capacity of Multi-Stage Flash Evaporation, Multi-Effect Distillation, and Mechanical Vapour Compression, Seawater and Brackish water Reverse Osmosis and Electrolyses Desalination plants in order to give an indication of the construction costs of these types of desalination techniques, based on plant capacity.

In 2008, Wittholz et al. developed a capital cost model based on data that had been collected from 331 desalination plants in a period of 35 years from 1970 to 2005 (Wittholz et al., 2008). The data included different desalination processes, such as MSF, MED, MVC, SWRO, BWRO, and ED. The collected data was adjusted to 2005 (paper writing time) using a cost index. The plants with production capacity with less than 300 m³/day were eliminated. A power equation of the linear regression method was used to develop the model of the relationship of capital cost and plant installed capacity, based on desalination techniques, as follows:

$$C_{C\,i} = m_i\, ln(\,P) + K_i \qquad (2\text{-}10)$$

where $C_{C\,i}$ is the capital cost, m, is the coefficient values, P is plant capacity, K_i is the constant, and i symbolizes the type of desalination process. As an indication of the developed model's quality, R^2 was presented at 0.655, 0.907, 0.814, 0.718, and 0.88 for the ED, SWRO, BWRO, MSF, MED, respectively. However, in common with most other previous attempts, operation costs were excluded.

McGivney and Kawamura (2008) have developed curves and models of capital cost and annual operational cost and based on daily capacity MGD (millions of gallons per day) for the common sea water desalination plants such as MSF, MD, SWRO, and MVC. The data used in these estimations were collected from those published by a number of public agencies. The authors did not state the background of the data. The developed curves and models have different limitations in plant capacity that can be estimated, based on the desalination process, as follows: SWRO and MED from 10 to 150 MGD, MSF from 10 to 50 MGD, while MVC are from 1 to 10MGD.

$$C_{C\,i} = m_i\, P^{b_i} \qquad (2\text{-}11)$$

$$C_{O\,i} = m_i\, P^{b_i} \tag{2-12}$$

where C_c is the Capital cost, C_O is the annual operation cost, m, and b are the coefficient values, P is plant capacity, i symbolizes the type of desalination process. Apart from the lack of clarity about the source of the data, the fact that the models have limited validity as far as plant capacity is concerned limits its use in most situations. Also developing different models for capital and operating cost based on the annual time scale is unlikely to meet the budgetary needs of operators in Saudi Arabia, where decisions are made on a monthly basis.

Total unit cost estimates

Other efforts have been made by Zhou and Tol, when a cost model was developed using the data collected from desalination plants worldwide. (Zhou & Tol, 2005). The number of plants used in the model are 442 MSF desalination plants, from 1957 to 2001; 2514 RO desalination plants from 1970 to 2001; 143 MED desalination plants; 289 VC desalination plants and from 427 ED desalination plants worldwide. The estimation of annual capital cost of each of these was based on an interest rate at 8% and plant life cycle of 30 years. According to the developers, there were not accurate data of operating cost that can be used in this cost modelling, so the operating cost was assumed to be 60 % and capital cost 40% of the total unit cost. The unit cost was estimated based on the location, the year, the plant capacity and raw water quality as dummy variables. The developers used regression methods to develop the models of each type of desalination technique with minimized sum of the squared residual. The final model was:

$$TUC_i = m_i \ln(\,P) + K_i + D \tag{2-13}$$

where TUC_i is the total unit cost, m_i, is the coefficient value, P plant capacity, K_i is a constant, D is the dummy variable (year, raw water salinity, region), and *i* symbolizes the type of desalination process. The coefficient of determination (R^2) varied from 0.6 in the MVC desalination plant to 0.88 in the MED desalination plant. The developers did not mention any validation attempt that has been carried out on the developed models. Also the arbitrary allocation of total cost between capital and operation is a major flaw of the method.

Dore (2005) used a statistical forecasting technique called the Autoregressive Integrated Moving Average Model (ARIMA) in order to anticipate the change in unit cost of an RO desalination plant in the near future on time series (Dore, 2005). The original data used in this model was the unit cost of desalted water published in 1985 by the US office of technology assessment for water treatment. Like Zhou & Tol, Dore estimated the annual capital cost based on interest rate at 8% and plant life cycle of 30 years; there was no consideration of operation cost. The model was developed with 95% upper and lower confidence intervals of the unit cost forecast. The equation of the model was:

$$(1 - B)\, TUC_t = -.31149899 + v_t - .80700050\, v_{t-1} \qquad (2\text{-}14)$$

where TUC_t is the unit cost at time t, v_t is the error at time period t, v_{t-1} is the error at time period t-1, and B is backward shift operator, i.e. $B(TUC_t) = TUC_{t-1}$ (Box and Jenkins, 2008). As a validity step test after the development step, the final model was applied on the actual cost of desalination plants in Israel (Ashkelon, and Kibbutz plants), Singapore and United Arab Emirates (Fujairah plant) in 2002. The results showed that the unit cost of these plants were located within the forecast range of the ARIMA developed model.

Lamei et al. (2008) developed a stochastic model to estimate unit production cost of the RO sea water desalination plant. They collected actual data from 21 plants (among them 14 plants located in Egypt). The plants' installed capacity varied from 250-50,000 m^3/ day. The cost was estimated based on operation and capital cost. The operation costs used are actual cost of average daily production in

2001. The capital cost was estimated based on 20 years lifetime and 8% interest rate and the estimate based on the amortization factor (see Equation 2-6). The plant production was assumed to be 90% of total installed capacity. The final developed model was:

$$TUC = 6.25\, P^{-0.17} \tag{2-15}$$

where TUC total unit cost (US$/ m^3) and P total water production (m^3/ day). The coefficient of determination (R^2) of the developed model was 0.55.

more recent research to develop cost modelling has also been undertaken to estimate unit cost (m^3) in RO desalination plants by Feo et al., (2013). The data used in this study was collected from small RO desalination plants in the Canary Islands (Spain). The capacity of these plants is between 500 to 15,000 m^3/day. The model used multiple regression, considering minimization of the least squares principle. Outliers were eliminated as the first step of the model development process. The final model was:

$$TUC = 10{,}383 + 0.326\, A + 0.018\, R + 21.059\, F + 0.033\, M + 0.963\, P + 2.214\, MO + 1.416\, MA + 0.806\, E \tag{2-16}$$

where A is amortization cost, R reagent consumption cost, F replacement cartridge filters cost, M membrane replacement cost, P staff cost, MO maintenance cost, MA environmental cost, and E energy consumption cost. All the costs were evaluated at Euro per cubic meter (€/ m^3). The model result was compared with 5 results of unit cost obtained from a running RO desalination plant with capacity 5000 m^3/ day, which is in the range of collected data of the developed model. The results showed that the developed model gives an accuracy to more than 98.5% of actual desalted water cost.

On the other hand, Kim et al.(2009a) have developed a process model of the Fujairah SWRO plant in the UAE only. The data has been collected over four years from 2003. The model was a software program to estimate the total profit of the Fujairah plant, based on the costs of membranes, process pumps, an energy recovery device, electricity, respectively, and income cash flow from selling the product water. The estimating of each of these costs is dependent on the operation parameters and efficiency of the membrane, process pumps and recovery device.

Software tools estimates

Some other efforts also have been made to provide a cost estimation program and software tools. One of the most well-known is WTCost (Waston et al, 2003). This is a computer program, developed by the Bureau of Reclamation, Irving Mach and Associates, and Boulder Research Enterprises. The model contains cost algorithms of membrane desalination systems, such as reverse osmosis and nano-filtration. The inputs of the program include water analyses, energy and chemical usages and prices, labour staffing and rates, construction indices, and amortisation. The outputs are capital and operation costs. The capital costs are estimated, based on the historical data of actual bids, while the operating costs are based on records of plants in service in the United States in the year 2000. The evaluation of costs based on a database of constructed membrane desalination plants has been included in the program. In 2004, WT Cost program was further developed by the Bureau of Reclamation to WT CostII. The main development was the addition of thermal process desalination techniques such as MSF, MED, and MVC as alternatives of the program run option (Irving et al. , 2008).

An other off-the-shelf example programs is the Desalination Economic Evaluation Program (DEEP), developed by the International Atomic Energy Agency in 1997 to carry out economic analysis and estimate the cost of a desalination plant based on different types of fuel and desalination techniques (Younos, 2005; DEEP Manual, 2003). The input data needed to use this program are general specifications, such as plant location, inlet sea water salinity, type of desalination technology, plant capacity. The program output includes energy consumption, product water flow rate, product water TDS, and water cost.

A comparison of some of the existing models is summarised in Table 2-5. In general, the majority of these prediction models, however, have been developed based on the construction cost (i.e. capital cost) only and do not undertake a more detailed evaluation of the operational costs, which are a significant part of the total water cost. Besides, because these models are largely empirical, relying for their calibration on data collected from specific countries, they are unlikely to be applicable in countries with different social-economic and other situations. The cost of energy or labour and technical criteria, i.e. sea water salinity, in Saudi Arabia, for example, would be expected to be radically different from that in the USA and Western Europe; thus, empirical models may not be interchangeable between these areas. Therefore, because of the specificity or the empirical nature of these models, they cannot be applied to Saudi Arabia plants with confidence. There is thus the need to develop bespoke prediction model for use in budget planning in Saudi Arabia.

Table 2-5 : Comparison of desalination cost models

Author, Year	Proposal	Data	Form	comment and Limitation
Watson et al., 2003	provide cost **curves** that contain linear relationship between capital and annual operation cost and plant capacity for different desalination techniques	N/A	N/A	• Commercial software • **Limitation**: The operating cost was assumed.
Zhou and Tol, 2005	Developed model to estimate total unit cost of RO, MSF, MED, VC, and ED based on total installed capacity of each of these desalination techniques	• Based on historical data of capital cost of 442 MSF plants, and 2514 SWRO, 143 MED, 289 VC, and 427 ED	$TUC_i = m_i \ln(P) + K_i + D$	• The developers used regression methods to develop the models of each type of desalination technique with minimize the sum of the squared residual • Annual capital cost estimated based on 8% interest rate and 30 years life cycle. • **Limitation**: The operating cost assumed at 60% and Capital cost 40% of total unit cost
Dora, 2005	Developing time series model to anticipate the change in unit cost.	Unit cost of SWRO plant published in 1985.	$(1-B)\,TUC_t = -.31149899 + v_t - .80700050\,v_{t-1}$	• used a statistical forecasting technique called the Autoregressive Integrated Moving Average Model (ARIMA) • The model developed with 95% upper and lower confidence intervals of the unit cost forecast • the final model was applied on the actual cost of desalination plants in Israel (Ashkelon, and Kibbutz plants), Singapore and United Arab Emirates (Fujairah plant) in 2002 • Annual capital cost estimated based on 8% interest rate and 30 years life cycle. • **Limitation:** there was no consideration of operation cost, considered RO plants only.
Wittholz et al., 2008	Developing model to estimate capital cost of different desalination techniques include MSF, MED, SWRO, BWRO, and ED	• From 331 desalination plants in a period of 35 years from 1970 to 2005. • A plant that less than 300 m^3/ day was eliminated.	$C_{C\,i} = m_i\, ln(P) + K_i$	• The collected costs were adjusted to 2005 using cost index. • A power equation of liner regression method used to develop the model of the relationship of capital cost and plant installed capacity • **Limitation:** operation costs were excluded.

Table 2-5: contd…

Author, Year	Proposal	Data	Form	Comment and Limitation
McGivney and Kawamura, 2008	Developing curves and models of capital cost and annual operational cost based on daily capacity production for a plant that used MSF, MD, SWRO, and MVC desalination techniques.	The developed curves and models have different limitation in plant capacity that can be estimated based on desalination process as follows: SWRO and MED from 10 to 150 MGD, MSF from 10 to 50 MGD, while MVC from 1 to 10 MGD.	$C_{C\,i} = m_i\, P^{b_i}$ $C_{O\,i} = m_i\, P^{b_i}$	• used regression methods to develop the models of each type of desalination technique • **Limitation:** the models have limited ability as far as plant capacity limits to use in most situations. Also developing different models for capital and operating cost also based on the annual time scale.
Kim et al, 2009	Developed a process model program of Fujairah SWRO to estimate the cost and total profit.	collected over four years from 2003	N/ A	• The model was a software program to estimate the total profit of Fujairah plant, based on the cost of membranes, process pumps cost, and an energy recovery device cost, electricity cost, and income cash flow from selling product water **Limitation**: considered RO plants only, The data has been collected from one plant (Fujairah)
Lamei et al, 2008	Developed a stochastic model to estimate unit production cost of RO sea water desalination plant	• collected actual data from 21 plants (among them 14 plants are located in Egypt) • The Operation costs used are actual cost of average daily production in 2001 • The plant's installed capacity varied from 250-50,000 m³/ day	$TUC = 6.25\; P^{-0.17}$	• Annual capital cost estimated based on 8% interest rate and 20 years life cycle. • The plant production assumed to be 90% to total installed capacity • **Limitation:** 14 from 21 plants used in data collection located in one country (Egypt), considered RO plants only, the production of the plants was assumed.

Table 2-5: contd…

Author, Year	Proposal	Data	Form	Comment and Limitation
Feo et al., 2013	Developed cost modelling to estimate unit cost (m^3) in RO desalination	• collected from small RO desalination plants in the Canary Islands (Spain) • capacity of these plants is between 500 to 15,000 m^3/day	$\mathrm{TUC} = 10{,}383 + 0.326\,\mathrm{A} + 0.018\,\mathrm{R} + 21.059\,\mathrm{F} + 0.033\,\mathrm{M} + 0.963\,\mathrm{P} + 2.214\,\mathrm{MO} + 1.416\,\mathrm{MA} + 0.806\,\mathrm{E}$	• Developed multiple regression model considering minimization of the least squares principle. • The outlier values were eliminated as the first step of model development process • The model was compared with 5 results of unit cost obtained from a running RO desalination plant with capacity of 5000 m^3/ day • **Limitation:** collected from small RO desalination plants in the Canary Islands (Spain).
Bureau of Reclamation, 2003	• A computer program called WTCost • Estimation of the capital and operation costs of membrane desalination techniques	• Only for RO desalination plant	N/A	• Commercial software • **Limitation:** Only for RO desalination plant.
Bureau of Reclamation et al., 2008	• A developed computer program of WTCost called WTCostII • Estimation of the capital and operation costs of membrane and thermal desalination techniques	N/A	N/A	• Commercial software

2.4.7. Monthly Models Development

The planning analysis must be based on a monthly time series, as has been discussed in Chapter One. In the current research, the hydrology of stochastically synthesized monthly flow will be used to estimate monthly costs. In general, there are two approaches which have been used for stochastically synthesizing monthly flow (McMahon & Adeloye, 2005): (i) Generate monthly flows directly using an appropriate monthly model, e.g. the Thomas-Fiering time series model and (ii) Disaggregate total annual flow into monthly flows e.g. Proration Method and Method of Fragments.

Thomas-Fiering time series model

The Thomas-Fiering time series model is used for stochastic generation of time series of annual and seasonal flows (i.e. monthly stream flows) (Montaseri & Adeloye, 1999). It was developed by H. Thomas and M. Fiering in 1962 for generation of monthly data. There are many reports of successful applications of Thomas-Fiering model to generate monthly streamflow data. For example, the effort has been made by Montaseri and Adeloye, when monthly flow data records were generated to compare reservoir system in two different climatic regions, Iran and England (Montaseri & Adeloye, 1999). The algorithm for this seasonal (month) model is as follows (McMahon & Mein, 1986; McMahon & Miller, 1971):

$$X_{i+1} = X^*_{j+1} + b_j\left(X_i - X^*_j\right) + t_i S_{j+1}\sqrt{(1 - r_j^2)} \qquad (2\text{-}17)$$

where X_{i+1}, X_i = generated flow during $(i+1)^{th}$, i^{th} seasons (months) reckoned from the start of the synthesizer sequencer ,

X^*_{j+1}, X^*_j = mean flow during $(j+1)^{th}, j^{th}$ months within a repetitive annual cycle of months, $1 \leq j \leq 12$

b_j = least squares regression coefficient for estimating $(i+1)^{th}$ flow from the j^{th} flow

$$b_j = r_j \frac{s_{j+1}}{s_j} \tag{2-18}$$

t_i = normal random variate with mean of zero and standard deviation of one,

S_{j+1}, S_j = standard deviations of flows during the $(j+1)^{th}, j^{th}$ months, and

r_j = serial correlation coefficient between flows in $(j+1)^{th}$ and j^{th} months.

In general The Thomas-Fiering model is used to estimate the generated values of stream flow based on three terms. The first one is the mean flow of historical data X^*_{j+1} during $(j+1)^{th}$. The second is the measure of the variation of the generated previous value X_i of X_{i+1}during i^{th} and the mean of historical value X^*_j during j^{th}. And the third is the measure of the variety of the serial correlation of historical mean of X^*_{j+1}, and X^*_j during $(j+1)^{th}$and j^{th}.

To apply the above model to generate monthly flows at a desalination plant, monthly mean, standard deviation and serial correlation coefficient are necessary. These statistical measurements are obtained from analysis of monthly historical flows.

To run the model, the flow in the first month X_1 will be the average flows of January months in the historical data X^*_{JAN}. Subsequent monthly flows are then as per the Thomas-Fiering seasonal model, as follows:

$$X_2 = X^*_{FEB} + b_{FEB/JAN}\left(X_1 - X^*_{JAN}\right) + t_1 S_{FEB}\sqrt{(1 - r^2_{FEB/JAN})} \qquad (2\text{-}19)$$

$$X_3 = X^*_{MAR} + b_{MAR/FEB}(CX_2 - X^*_{FEB}) + t_2 S_{MAR}\sqrt{(1 - r^2_{MAR/FEB})} \qquad (2\text{-}20)$$

$$\downarrow$$

$$X_{13} = X^*_{JAN} + b_{JAN/DEC}(X_{12} - X^*_{DEC}) + t_{12} S_{JAN}\sqrt{(1 - r^2_{JAN/DEC})} \qquad (2\text{-}21)$$

Proration Method

The proration disaggregation method is a simple technique in which annual flows are disaggregated based on the historical monthly percentage of the long-term mean annual total value occurring in each month (McMahon & Adeloye, 2005). To apply this method, both the annual mean and the monthly mean flows will have to be estimated from the historical data. The the ratio of the monthly mean μ_j to the annual means μ_A is defined as follows:

$$Rat_j = \frac{\mu_j}{\mu_A} \quad , \quad j = 1, 2, \ldots, 12 \qquad (2\text{-}22)$$

The generated annual rainfalls are disaggregated by multiplying the ratio Rat_j for each month from January to December by the year that does not have monthly readings, to obtain them.

Method of Fragments

The method of fragments (MOF) was first proposed by Svanidze in 1964 as a way of disaggregating of annual runoff data into monthly data by selecting the appropriate fragment from the historical data.

In this method, the observed monthly flows are standardised year by year so that the sum of the monthly flow in any rainfalls equals to unity. This is carried out by dividing the monthly flow in a year by the corresponding annual flow. By doing so, from a record of n years, one will have n sets of fragments of monthly flows. The appropriate monthly fragments for a given year, i, are selected by considering the closeness of the generated annual flow data and the monthly flow for the last month of the previous year of the already disaggregated data to the corresponding historical values (McMahon & Adeloye, 2005; McMahon & Mein, 1986). A major limitation of this procedure is that the monthly correlation between the first month of a year and the last month of the previous year will not be preserved (Silva & Portela, 2012; Srikanthan & McMahon, 2001), which is not a problem in current research, since the research analyses the costs of water, not flows. On the other hand, the method of fragments is not suitable, as the flow data comprises a number of months of no flow (Srikanthan et al., 2002)

The fragments of historical monthly data from annual data were estimated using equation 5-1.

$$Fx_{j,i} = X_{j,i} / X_i \qquad (2\text{-}23)$$

$i = 1, 2, ..., N;\ j = 1, 2,....., 12$

where $x_{j,i}$ is the historical monthly flow for month j, year i, and X_i is the total annual flow in year i and $Fx_{j,i}$ are referred to as the fragments of month j, year i.

After estimating the fragments using the available, complete historical annual monthly data, these fragments will then form the basis for disaggregating the annual flows that do not have monthly flows. However, an important aspect in the method of fragments is the way of selecting the appropriate fragment to apply to each of the annual value that is to be disaggregated (Silva & Portela, 2012).

There are three approaches which can be used to select the correct fragments which are explained in detail in section 5.3.

It can be seen from above steps that the method of fragments is similar to the proration method. The only difference is that the method of fragments used for distributing the generated annual flow are not constant fragments but vary with total annual volume flow. Consequently, the method of fragments as per McMahn and Adeloye performed slightly better than the proration method (McMahon & Adeloye, 2005).

2.5. Summary

This chapter introduced the background to the water resources of the Saudi Arabia. It presented an introduction to Saudi Arabia and its general climate, with brief information about the geographical features, economic systems and administrative territorial entities of Saudi Arabia. It also comprised a review of water resources, water demand, and water management institutions in Saudi Arabia. Sea water desalination plants and their configuration of parts, and their situation in Saudi Arabia were described in detail. Costs of water production from seawater desalination plants and factors affecting the cost of production from desalination plants were also reviewed. Finally, the chapter ended with a review of predictive models of water cost from desalination plants that have been developed in previous studies. Because these existing models are restricted in their scope and types of cost considered, they could not be applied directly to Saudi Arabia situation.

Chapter 3 - Methodology

3.1. Introduction

As discussed in previous chapters, there is limited conventional water resources in Saudi Arabia, which is thus forced to use sea water desalination plants to cover the shortage in drinking water. There is also a change of water demand, owing to the acceleration of Saudi population growth, which requires it to construct new desalination plants. One of the major problems facing countries who use desalination technologies to cover their gap in drinking water is the high cost of the desalination. Several factors affect the cost and it will be possible to budget properly if the relevant factors that determine the overall cost are identified and understood precisely and used to develop a cost predictive model.

The methodology adopted for the research is illustrated in the flow chart in Figure 3-1. As shown in the Figure, there are five distinct components to the study, viz: data collection; data pre-processing; correlation study; model development including validation; and the assessment of uncertainty using Monte Carlo simulation. Detailed description of the individual components in the following sub-sections. Generally, companies forecast their budgets based on the monthly cash forecasting, for which accuracy of various cost estimations is one of the most important issues (Brigham & Ehrhardt, 2005; Hilton, 2005). Therefore, to develop useful predictive models, the data input must be based on monthly values. Six factors have been investigated in this monthly development model, which are (i) monthly total water production, (ii) average monthly seawater total dissolved solids, (iii) average monthly product water total dissolved solids, (iv) average monthly energy consumption for producing one m^3 of distillate water, (v) type of desalination technique and, of course, (vi) monthly unit cost of water production.

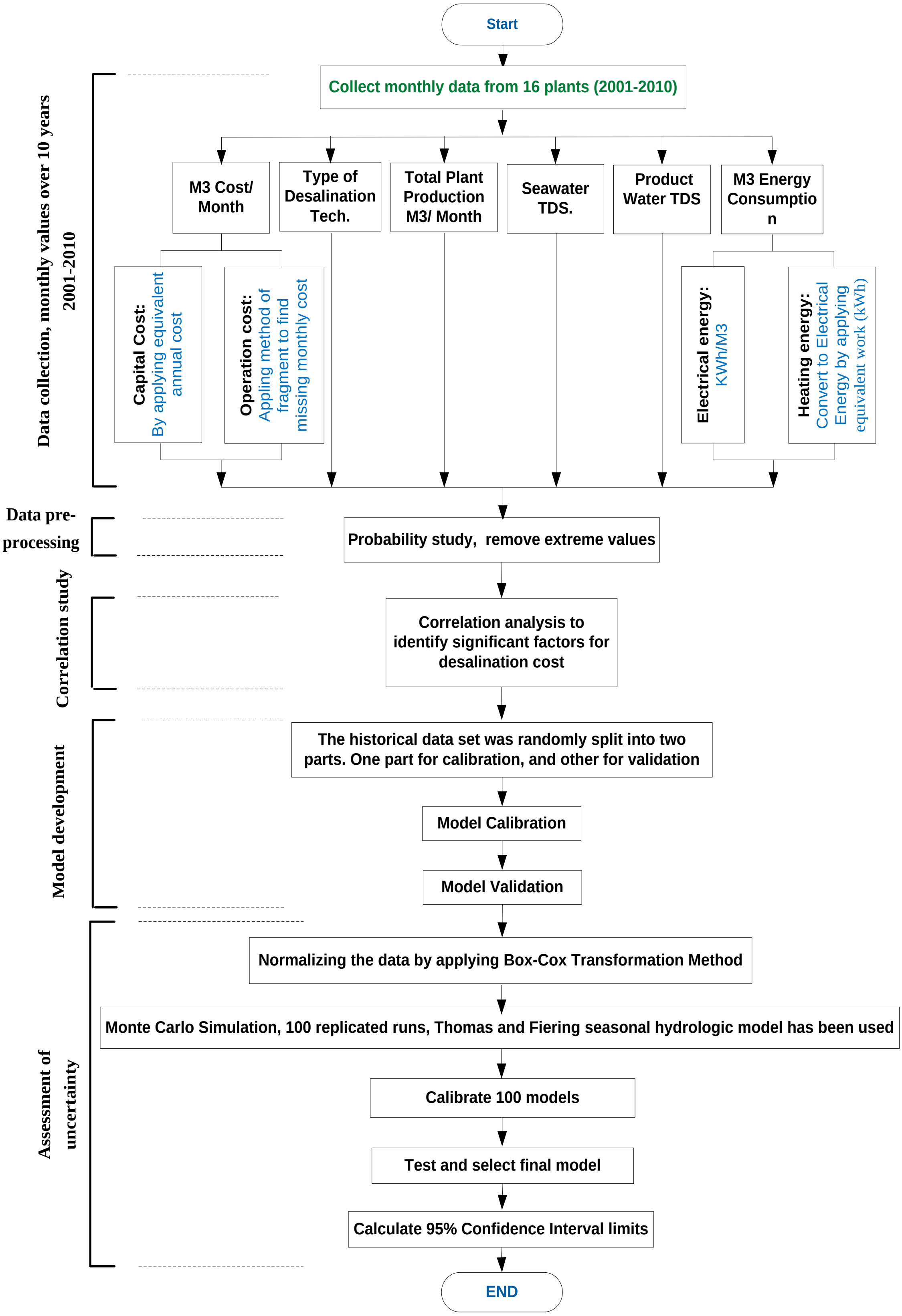

Figure 3-1: Research methodology overview.

3.2. Data Collection

3.2.1. Summary of the Desalination Plants

The main seawater desalination plants in Saudi Arabia, with a production capacity of more than 50,000 m³ per day, have been selected for this research. These plants are: Jubail 1, Jubail 2, Jubail RO, Khobar 2, Khobar 3, Jedah 2, Jeddah 3, Jeddah 4, Jeddah RO1, Jeddah RO2, Shouba 1, Shouba 2, Yanba 1, Yanba 2, Yanba RO1, and Shoqiq. The main characteristics of the desalination plants are summarised in Table 3-1. These plants are located in six locations or cities. The names of these plants refer to the city name, while the number refers to the plant's number for each city. All these plants are under the management of the Saline Water Conversion Corporation (SWCC), which is the main organisation responsible for operating and maintaining the seawater desalination plants in Saudi Arabia, see section 2.2.4. All of them are co-generation plants producing water and electricity as explained in section 2.5.4. These plants provided approximately 98% of the total water production from sea water desalination plants in the Kingdom during the period 2000-2010. Jeddah 1 and Khobar 1 which were commissioned in 1970 and 1973 respectively were closed down in 1983 (SWCC, 2006).

As shown in Table 3-1, the plants use one of two different desalination technologies: reverse osmosis (RO) or multi stage flash (MSF). Jeddah RO1, Jeddah RO2, Yanbu RO1, and Jubail RO1 use the reverse osmosis (RO) desalination technique. Among them, the largest installed capacity is that of Yanbu RO1, at 128,182 m³/ day. The other desalination plants use the multi-stage flash technique (MSF). Jubail 2 has the largest installed capacity of the MSF desalination plant in Saudi Arabia at 947,890 m³/ day and 40 MSF desalination units, each one of which can produce 23,697 m³/ day. The biggest MSF units are located in Shuiba 2 plant where each unit produces 45,455 m³/

Table 3-1: Desalination plants studied in this research.

Plant	Coast	Desalination technique	No. Of units	Unit installed capacity (m³/ Day)	Total Installed Capacity (m³/ Day)	Total Installed Capacity (m³/ Month)	Start of production	Years in service	Capital cost, SR (Saudi Riyals)
Jubail 1	Arabian Gulf	MSF	6	22,955	137,729	4,131,870	1982	28	1,135,734,000.00
Jubail 2	Arabian Gulf	MSF	40	23,697	947,890	28,436,700	1983	27	5,325,488,100.00
Jubail RO	Arabian Gulf	RO	....	....	90,909	2,727,270	2001	11	945,964,543.75
Khobar 2	Arabian Gulf	MSF	10	22,300	223,000	6,690,000	1983	27	1,535,564,400.00
Khobar 3	Arabian Gulf	MSF	8	35,000	280,000	8,400,000	2000	11	1,245,049,800.00
Arabian Gulf (Eastern Coast)					**1,679,528**	**50,385,840**			10,187,800,843.75
Jeddah 2	Red Sea	MSF	4	11,022	44,088	1,322,640	1978	29	352,681,710.00
Jeddah 3	Red Sea	MSF	4	22,089	88,357	2,650,710	1979	31	778,115,592.75
Jeddah 4	Red Sea	MSF	10	22,158	221,575	6,647,250	1982	28	1,299,364,806.50
Jeddah RO - 1	Red Sea	RO	....	....	56,800	1,704,000	1989	22	183,537,186.54
Jeddah RO - 2	Red Sea	RO	....	....	56,800	1,704,000	1994	17	375,287,058.21
Yanbu 1	Red Sea	MSF	5	21,615	108,074	3,242,220	1981	29	651,407,481.05
Yanbu 2	Red Sea	MSF	4	36,000	144,000	4,320,000	1998	13	1,204,120,069.00
Yanbu RO	Red Sea	RO	....	....	128,182	3,845,460	1998	13	878,040,820.75
Shuiba 1	Red Sea	MSF	10	22,300	223,000	6,690,000	1989	22	1,589,418,572.50
Shuiba 2	Red Sea	MSF	10	45,455	454,545	13,636,350	2001	10	1,931,801,599.29
Shugaig	Red Sea	MSF	4	24,254	97,014	2,910,420	1989	22	501,140,080.96
Red Sea (Western Coast)					**1,622,435**	**48,673,050**			9,744,914,977.55
Total					**3,301,963.00**	**99,058,890**			**19,932,715,821.30**

day. Shuiba 2 is a relatively new desalination plant, which started production in 2001, while the oldest one is the Jeddah 2 MSF desalination plant which started production in 1978 and closed down in 2008. All the MSF plants are still in service, except Jeddah 2.

Four types of data sources are used in this research. The first source is the annual report of the maintenance and operation sector of SWCC over eleven years (2000- 2010). The second source is the production information system (PIS) in SWCC, which has been updated daily by operation staff. The third source is the operation and maintenance manuals of the plants. The fourth source is the monthly cost report of the finance department.

3.2.2. Collected data

The data collected cover all 16 desalination plants over a period of ten years from 2001-2010. These comprise: total water production (TWP); sea water salinity (SWTDS); produced water salinity (PWTDS); Steam to brine heater in MSF desalination plant; running hours; electrical power consumption; the type of desalination techniques (DT); monthly operation cost and construction cost. These data have been rigorously subjected to quality checks by the SWCC and are summarised in Table 3-2.

As seen in Table 3-2, although all the annual values for the variables are available, some of the monthly values are unavailable.

Table 3-2: Summary of the data collected**.**

Plant	Steam to B.H (ton)/ Month	Total Water Production (m^3)/ Month	Running Hours/ Month	Power consumption MW/ month (Electricity)	Sea Water TDS (ppm)/ Month	Product Water TDS (ppm)/ Month	Operation Cost (SR))/ Month	Cot of data availability	
								Annual	Monthly
Khobar-2	895,508.5	4,791,108.3	6,279.9	N/A	50,922.6	88.9	10,424,067.0	2001-2010	2005-2008
Khobar-3	1,220,409.7	7,831,784.4	5,493.4	N/A	51,151.2	13.1	10,368,811.7	Ditto	Ditto
Jubail-1	432,549.4	3,630,245.9	3,257.5	N/A	42,659.7	1.6	7,781,509.1	Ditto	Ditto
Jubail-2	3,490,744.9	27,935,784.7	26,198.0	N/A	42,659.7	14.2	36,689,740.1	Ditto	Ditto
Jubail-RO	0.0	1,086,686.9	N/A	10,657.4	42,659.7	628.0	4,578,501.0	Ditto	Ditto
Yanba-1	293,877.9	2,826,383.8	3,283.3	N/A	41,635.8	18.4	5,205,034.1	Ditto	Ditto
Yanba-2	415,731.1	3,437,943.2	2,539.0	N/A	41,635.8	16.6	4,217,585.7	Ditto	Ditto
Yanba-RO	0.0	3,461,768.3	N/A	23,617.5	44,081.9	296.3	4,906,284.0	Ditto	Ditto
Jeddah-2	72,242.1	648,834.3	1,931.0	N/A	37,900.4	537.4	3,077,382.7	Ditto	Ditto
Jeddah-3	398,737.0	2,244,560.4	2,704.8	N/A	37,900.4	106.1	5,103,506.0	Ditto	Ditto
Jeddah-4	747,882.6	5,541,398.2	6,255.0	N/A	37,900.4	108.8	11,915,973.1	Ditto	Ditto
Jeddah-RO1	0.0	1,835,185.4	N/A	14,242.1	37,900.4	770.3	3,721,344.2	Ditto	Ditto
Jeddah-RO2	0.0	1,941,815.9	N/A	13,773.2	37,900.4	264.4	2,384,429.3	Ditto	Ditto
Shouba-1	717,576.7	6,386,818.9	6,453.0	N/A	37,750.0	74.3	9,429,726.2	Ditto	Ditto
Shouba-2	1,474,704.5	12,800,283.6	7,120.4	N/A	37,750.0	49.5	10,017,738.7	Ditto	Ditto
Shoqiq	401,129.5	3,078,835.7	2,819.9	N/A	39,110.2	19.2	6,014,661.8	Ditto	Ditto

3.2.2.1. Cost Data

Because not all the monthly values were available, only the annual cost data will be discussed in this section. The detailed discussion of the monthly data will be delayed until chapter 5 when the methodology for infilling the missing monthly data values will be described. Also, for brevity and based on the data availability, the discussion of the costs distribution will be based on location instead of individual plants. Thus rather than discuss costs for each of the 16 plants, they will be lumped into the 6 locations of Jubail, Khobar, Jeddah, Yanbu, Shuiba and Shugaig.

The total operation cost of distillate water produced from seawater desalination plants in Saudi Arabia is variable from year to year, as in any other industry. For example, as shown in Figure 3-2, the average operation annual cost in eleven years increased from 1.59 SR/m^3 in 2000 to 2.47 SR/m^3 in 2010, with a minimum of 1.45 SR/m^3 in 2003. This observed trend is due to two reasons. The first reason is water production, which increased dramatically from 2.08 million m^3 per day in 2000 to 2.93 million m^3 per day in 2004, as a result of the commissioning of new plants at Shouba2, Khobar3, and Jubail RO. However, this increased was offset by the economy of scale achieved in the operation and maintenance cost, causing the total operation cost to decrease from 1.59 SR/m^3 in 2000 to 1.45 SR/m^3 in 2003. The second reason is that, due to the rehabilitation and life extension for the existing plant, as well as the development projects in the Saline Water Conversion Corporation (SWCC), the maintenance cost as well as the administrative cost went up within six years from 0.29, and 0.26 SR/ m^3 in 2004 to 0.87 and 0.57 (SR/ m^3) in 2010 respectively. This variability is due to rehabilitation and life extension projects for the existing plants, which led to increased maintenance work (spare parts and manpower) and working hours of administration and supervision staff. In contrast, operation of many desalination units had been halted due to these rehabilitation and life extension projects, which resulted a reduction in total water production as mentioned in Figure 3-2.

The unit operation cost is the cost divided by the production capacity and this is summarised in Table 3-3 for all locations. The highest average production between 2000-2010 was from the Jubal plants, at 1,034,000 m³ / day, which is related to plant capacity. However, the best plant production, based on plant capacity, is the Shoqiq plant, at efficiency of 100%. Mostly this was because each of these high efficiency plants had worked with a shorter time period for annual maintenance shut-down (total of 2 weeks a year), which was less than predicted during the plant's design period (4 weeks a year) (SWCC, 2011). In terms of running costs (operation staff, fuel, and chemical), the best running cost was in the Shuiba plants, which was 0.78SR/ m³ while the highest running cost was 1.05SR/ m³ in the Jeddah desalination plant. With respect to average maintenance cost, the lowest cost was also in the Shuiba plants, at 0.23SR/ m³ and the highest was in the Jeddah plants, at 0.66SR/ m³. In general, the best total unit operation cost was in the Yanba plants, at 1.27SR/ m³ and the highest was in the Shoqiq plant, at 1.981SR/ m³.

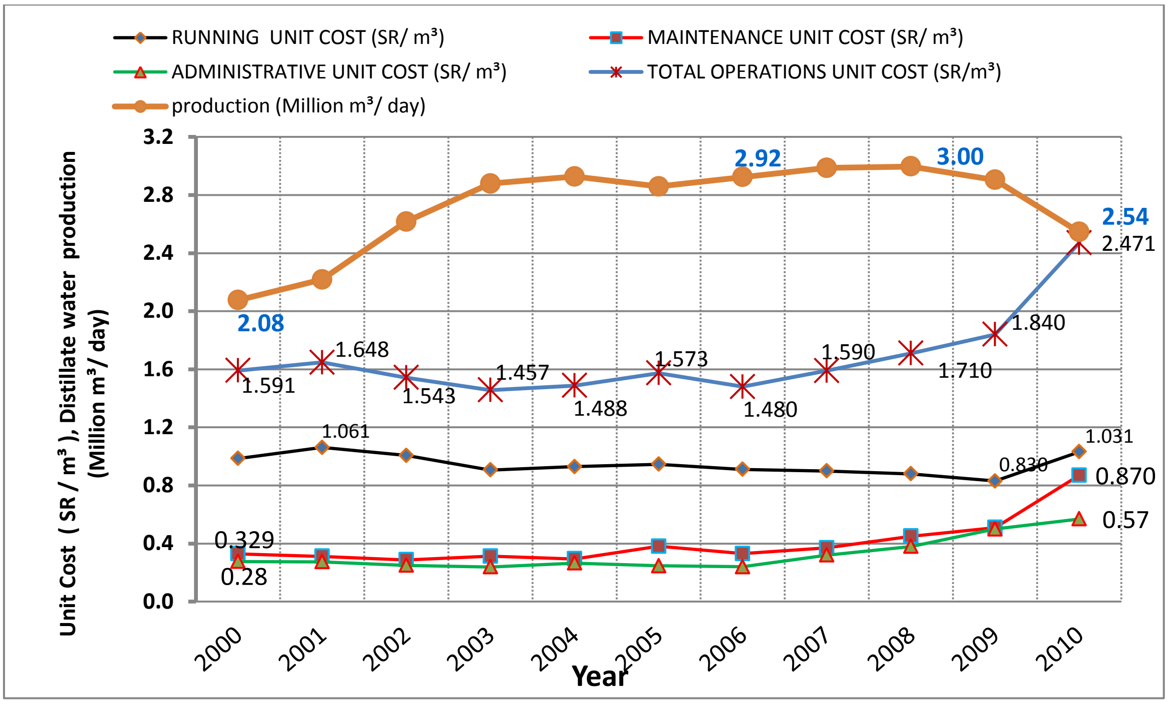

Figure 3-2: The distribution of costs of distilled water from seawater desalination plants in KSA (SWCC, 2000-2009)

The total capital costs are summarized in Figure 3-3, on which are also presented the aggregate production capacity of each of the locations. As expected, the capital cost increases as the plant capacity increases. Thus, the highest construction cost was Jubail plants at total cost 4.29 billion Saudi Riyal while the lowest cost was in Shoqiq plant at 0.35 billion Saudi Riyal.

Table 3-3: Summary of the operation unit cost.

Plant location	Average production, m³ / Day	Plant's efficiency %	Average Running cost (SR/ m³)	Average Maintenance cost (SR/ m³)	Average Administration cost (SR/ m³)	Average of total operation cost (SR/ m³)
Jubail	1,034,000	87.9	0.87	0.24	0.18	1.286
Khobar	350,000	69.6	1.02	0.38	0.29	1.695
Jeddah	396,000	93.5	1.05	0.66	0.42	1.72
Yanba	308,000	81.0	0.82	0.40	0.36	1.272
Shuiba	502,000	74.1	0.78	0.23	0.21	1.572
Shoqiq	97,000	100.0	1.03	0.35	0.61	1.981

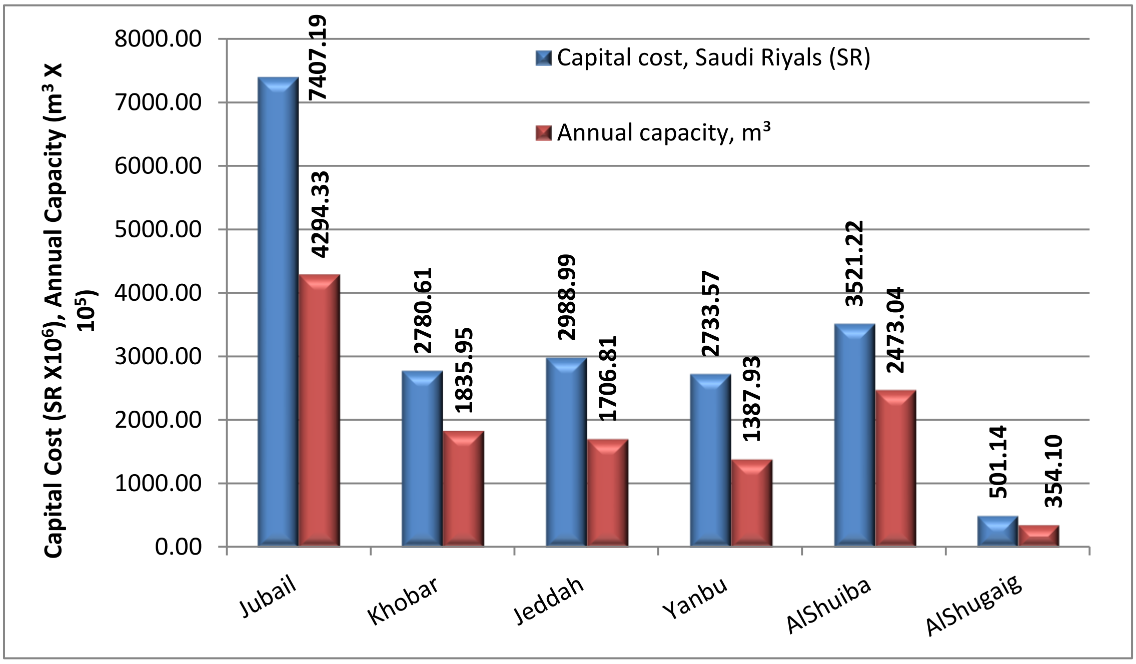

Figure 3-3: Total cost of construction at each location.

The modelling will utilise monthly costs and Figure 3-4 shows the availability of monthly cost data for the project. As shown in Figure 3-4, monthly operating costs are available only for years 2005-2008. Thus, the unavailable monthly operating costs will have to be estimated using method of fragments as described in Chapter 5. To obtain the monthly capital cost, first the annual capital cost will be estimated considering the time value of money, as will be discussed in Chapter 4. Once the annual capital cost is known, the monthly capital cost will be obtained by dividing the annual capital cost by 12.

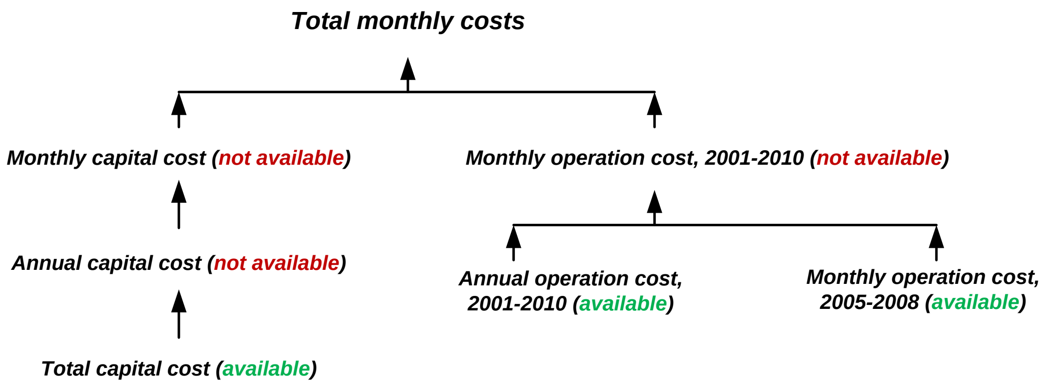

Figure 3-4: **Monthly cost data availability.**

3.2.2.2. Monthly water production

The monthly water production data are summarised in Figure 3-5. As shown in Figure 3-5, the total monthly water production is generally compatible with (i.e.$\leq$) the total installed capacity, except at Shugaig, Jeddah RO1 and Jedda RO2. The highest water production was in Jubail2, with an average of more than 28.4 x10^6 m^3 and the lowest was in Jeddah2, with 1.3 x10^6 m^3. Shugaig, Jeddah RO1, and Jeddah RO2 plants, with total installed capacity per month of 2.910 x10^6 m^3, 1.704 x10^6 m^3, and 1.704 x10^6 m^3, respectively recorded average monthly production of 3.034 x10^6 m^3, 1.797 x10^6 m^3 and 1.854 x10^6 m^3, respectively in the period 2001-2010. The reason for this high production is due to the high demand for drinking water and shortage of other water resources in the areas of these plants. Mostly each one of these high production plants had worked with less time period for annual maintenance shut down, less than expected in plants design period.

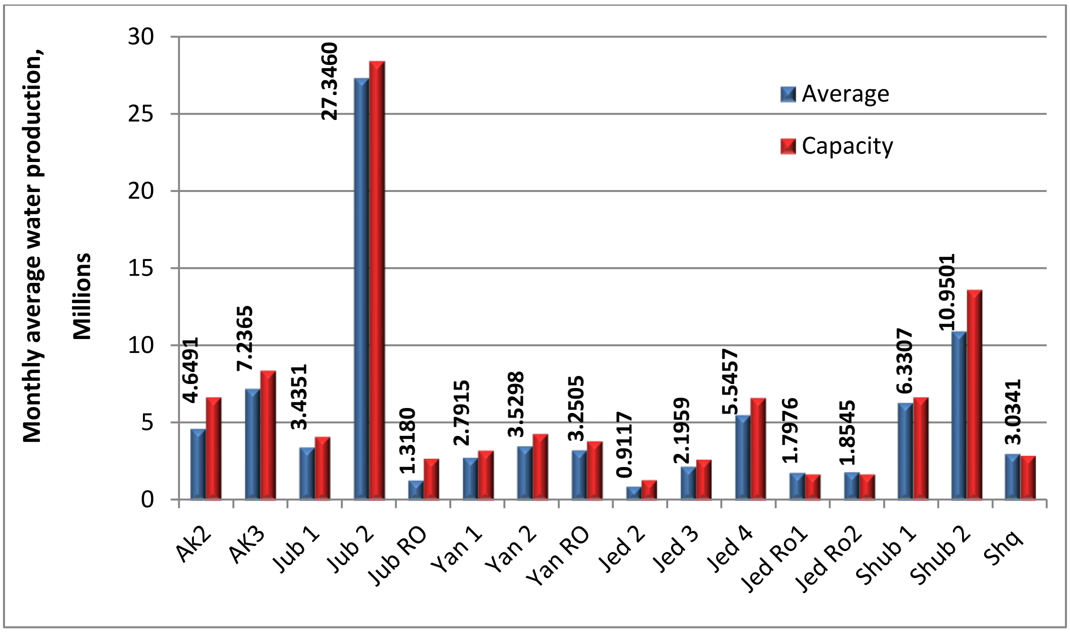

Figure 3-5: Monthly average water production of desalination plants 2001-2010.

3.2.2.3. Monthly sea water salinity

In terms of monthly records of the sea water salinity of plants, the quality of sea water varied between 51.49 x10^3 ppm at the Kohbar plants area to, at 37.75 x10^3 ppm at Shuiba plants (see Figure 3-6). In general, the average salinity of the Arabian Gulf, which feeds the Khobar and Jubail plants was 45.98 x10^3 ppm, which agrees with a previous study (Micale et al., 2009) , while the average salinity of the Red Sea, which feeds the rest of the plants was 39.88 x10^3 ppm.

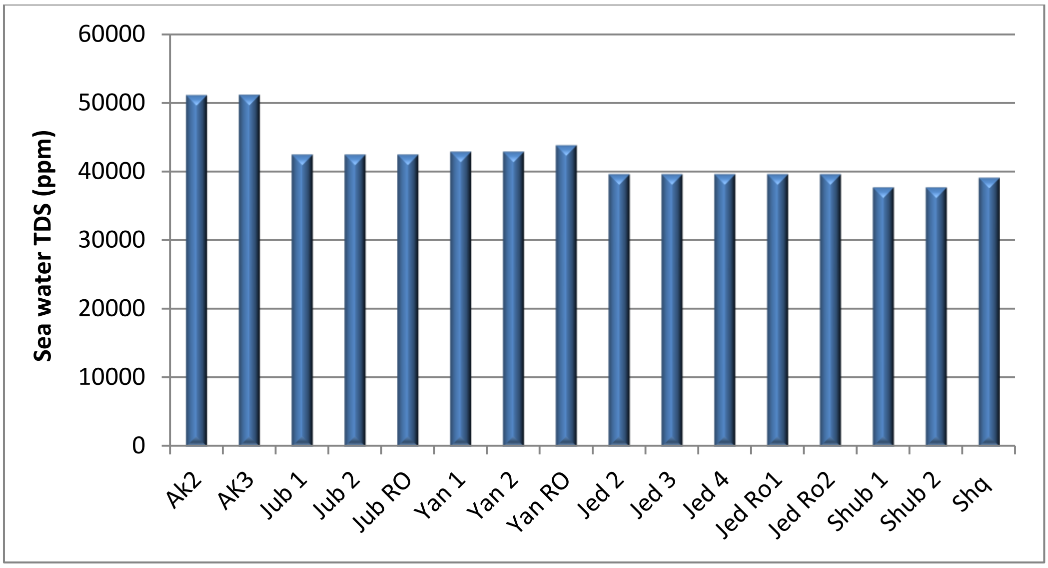

Figure 3-6: Monthly average sea water TDS 2001-2010.

3.2.2.4. Monthly produced water salinity

With respect to monthly records of produced water, the best quality of produced water was in Jubail 1 at TDS 1.6 ppm whereas the poorest quality was in Jeddah RO1 at TDS 653.5 ppm (see Figure 3-7). In general, the average salinity of produced water from MSF desalination plants was 84.09 ppm. In contrast, the average salinity of produced water from RO desalination plants was 496.1 ppm.

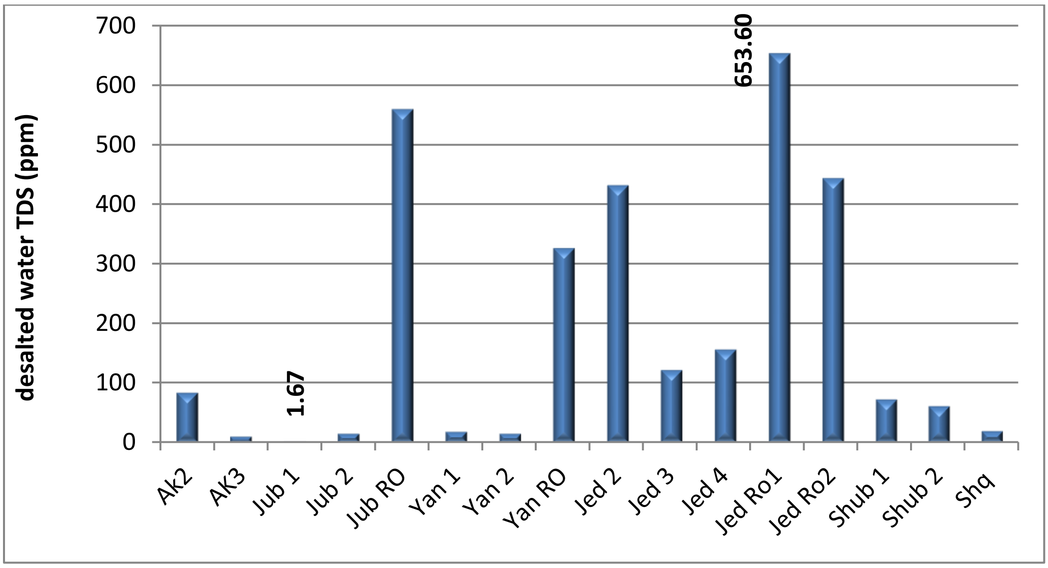

Figure 3-7: Monthly average produced water TDS 2001-2010.

3.2.2.5. Energy consumption

With regard to energy consumption, there was only a record of energy consumption for the RO desalination plants and this is summarised in Figure 3-8. In contrast, there was no record of total energy consumption in any MSF desalination plants and this was estimated from first principles since energy consumption is one of the factors of cost being investigated in the study.

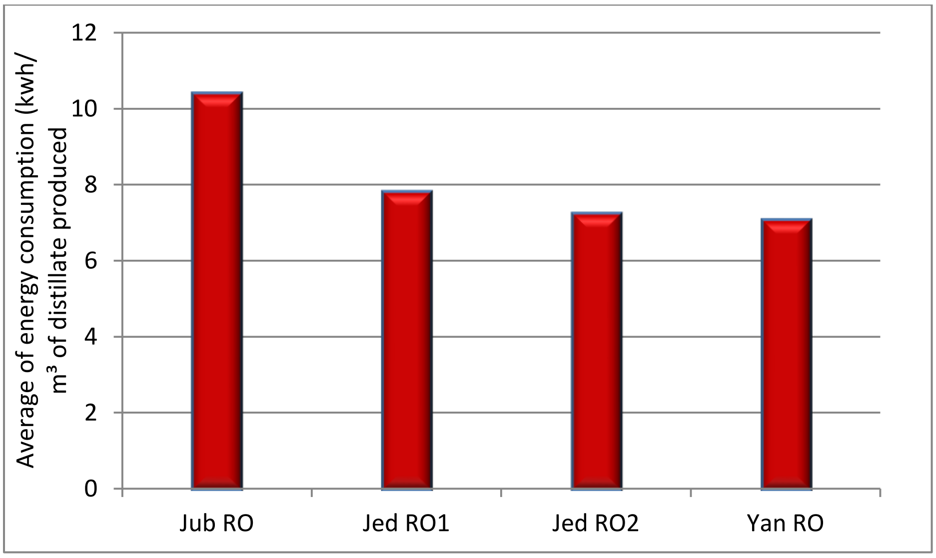

Figure 3-8: Energy consumption in for the RO desalination plants.

There are two types of energy consumption in MSF desalination plants. The first one is the heating energy, in the form of steam from the boiler, to heat up the brine water; the other energy is the electrical energy. To determine the heating energy consumption in the current study, the total amount of steam to the brine heater and the total steam consumption to the ejector system must be known. The total steam consumption of a month by ejectors has been determined by finding out the amount of steam consumed in one hour by the ejectors system and the total running hours of the desalination plant.

The electrical energy was determined by multiplying one hour's energy consumption of a plant by the total number of plant operating hours for each month, as shown in Figure 3-9. The final total energy consumption was estimated in equivalent kilowatt hours of electric energy per cubic meter, the heating energy was converted to electrical energy by applying equivalent work theory. Figure 3-9 is a schematic of the steps involved in the MSF energy consumption calculation. Because of the intricate nature of the associated calculations, chapter 6 has been developed to the subject.

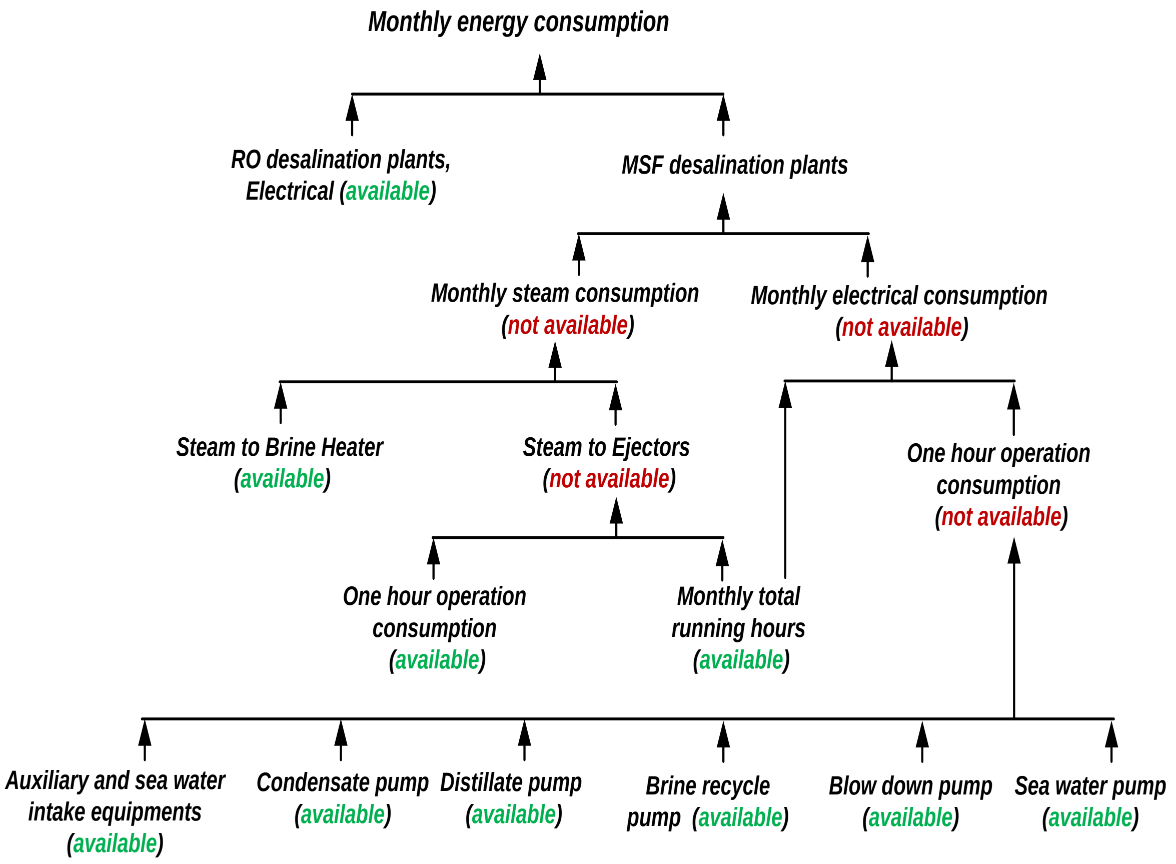

Figure 3-9: Energy consumption data availability in current study.

3.3. Data Pre-processing

3.3.1. Identification of Outliers

An outlier is a score very different from the rest of the data (Field, 2013; Rustum & Adeloye, 2007). One of the goals of carrying out the pre-processing was aimed at establishing the existence of outliers in the data and removing them before further analyses. For this purpose, the z-score approach was used, where the z-score is defined in equation (3-1). However, the outliers can also be recognized through graphic representation of the data with a histogram graph or a boxplot graph (Field, 2013).

$$Z = \frac{(X-\mu_X)}{\sigma_X} \tag{3-1}$$

$$\mu_X = \frac{1}{n}\sum_{i=1}^{n} X_i \tag{3-2}$$

$$\sigma_X = \sqrt{\frac{1}{n-1}\sum_{i=1}^{n}(X_i - \mu_X)^2} \tag{3-3}$$

where X is the observation, μ is the mean and σ is the standard deviation of the all collected readings (Field, 2013), and n- is sample size. As a rule, an observation with z-score of 2.58 or above, i.e. with less than 1% probability to occur based on the assumption of normality, is classified as an outlier and removed. The normality of the data has been assumed based on the assumption that cost cannot be negative and as requirement to apply z-score (Rustum & Adeloye, 2007), although there is a skewness in the cost values and the transformation method has been used to normalise these values as will be discussed later in section 3.4.1.

3.3.2. Correlation Study

As mentioned in methodology flow chart, after the data pre-processing, a correlation study was carried out to determine whether the factors that have been collected are correlated with water production cost or not. Since the current analysis is a quantitative research the Pearson correlation coefficient " r " has been used (Chok, 2010; Hauke & Kossowski, 2011; Rabie, 2008). The Pearson correlation coefficient is the ratio between the covariance of the two variables and the product of their standard deviations. as shown in equation (3-13) (Delorme, 2013).

$$r_{XY} = \frac{\frac{1}{n}\sum_{i=1}^{n}(X_i - \mu_X)(Y_i - \mu_Y)}{\sigma_X . \sigma_Y} \tag{3-13}$$

where r_{XY} is the Pearson correlation coefficient between variables X and Y, μ_X , σ_X and, μ_Y , σ_Y are the mean and standard deviation of variable X and Y respectively; n- sample size.

3.3.3. Infilling missing monthly data

As noted earlier, monthly data for some of the years are missing as detailed in Figure 3-8. A method to infill the record was also developed as part of the study. Essentially this involved several variants of the method of fragments that have been so successfully used in stochastic hydrology to obtain monthly data from annual totals (see McMahon and Adeloye, 2005). However, because of the volume of work involved in the disaggregation and its importance to the overall study, its details have been presented in a separate chapter.

3.4. Monte-Carlo simulation

3.4.1. Data Simulation Pre-Processing

A normality assumption is necessary for the subsequent Monte-Carlo simulation. As shown in Appendix E, most of the observed monthly data have a long tail on the left, which means these data have negative skew (Hippel, 2010). So, this has to be normalized before using the data for further Monte-Carlo simulation and generation of replicates of the observed data. One of the methods used for normalizing the data is the transformation method. The Box-Cox transformation method is used in this study to minimize the skewness and normalise the data, as discussed in the following section.

Box-Cox Ttransformations

The Box and Cox transformation method was developed by G. Box and D. Cox in 1964 to minimize the skewness and normalize an observed time series, X_t (Kottegoda, 1980).

$$Y_{j,V,P} = \frac{X_{j,V,P}^{\lambda} - 1}{\lambda} \qquad \text{If} \quad \lambda \neq 0 \tag{3-14}$$

$$Y_{j,V,P} = \ln\left(X_{j,V,P}\right) \qquad \text{If} \quad \lambda = 0 \tag{3-15}$$

where λ is the parameter that transforms the $X_{j,V,P}$ into the normal series $Y_{j,V,P}$ exhibiting minimum skewness, j represents the month of the year $1 \leq j \leq 12$, V is the variable (total water production or total unit cost), P represents the desalination plants. Matlab software was used to find the value of λ, as well as implement the Box and Cox transformation method. In stochastic model estimation, such as the current research, both dependent and independent variables can be transferred (Box & Cox, 1964). The last step in data simulation is to return the generated value to the original value by applying the inverse of the Box-Cox transformation method, i.e.

$$X_{j,V,P} = [\lambda * Y_{j,V,P} + 1]^{1/\lambda} \quad (3\text{-}16)$$

3.4.2. Stochastic data generation

In any operation system, there is a chance of uncertainty in any evaluation process. When modelling a system or evaluation process, the uncertainty will be reflected in the model parameters. The Monte-Carlo simulation method is a tool that can be used to reduce this uncertainty by developing by generating equally probable replicates of the historical data (Giri et al., 2001). It generally applies to all simulation processes that use stochastic methods to generate new formations of the system of interest based on generation of random variables (Earl & Deem, 2008; Rebort & Casella, 2004; Niederreiter, 1992) . Obtaining these random variables is the process called random number generation (Gentle, 2009). These random numbers are distributed over the interval (0-1) and usually are identically and independently distributed (Gentle, 2003).

After normalizing the observed data by the Box-Cox transformation method, the TWP and TUC monthly time series were replicated 100 times, using the Thomas and Fiering time series model to generate the replicates of data in this simulation (McLeod, 1993; McMahon & Mein, 1986).

Thomas-Fiering time series model

The Thomas-Fiering time series model is used for stochastic generation of time series of annual and seasonal (i.e. monthly stream flows) (Montaseri & Adeloye, 1999). It was developed by H. Thomas and M. Fiering in 1962 for generation of monthly data. It has been chosen in the current research because of its success and simplicity, to generated monthly data of the available historic records as mentioned in section 2.4. The algorithm for this seasonal (month) model is as follows (McMahon & Mein, 1986; McMahon & Miller, 1971):

$$C_{i+1} = C^*_{j+1} + b_j\left(C_i - C^*_j\right) + t_i S_{j+1}\sqrt{(1 - r_j^2)} \tag{3-17}$$

where C_{i+1}, C_i = generated cost during $(i+1)^{th}$, i^{th} seasons (months) reckoned from the start of the synthesizer sequencer ,

C^*_{j+1}, C^*_j = mean cost during $(j+1)^{th}, j^{th}$ months within a repetitive annual cycle of months, $1 \leq j \leq 12$

b_j = least squares regression coefficient for estimating $(i+1)^{th}$ cost from the j^{th} cost

$$b_j = r_j \frac{s_{j+1}}{s_j} \tag{3-18}$$

t_i = normal random variate with mean of zero and standard deviation of one,

S_{j+1}, S_j = standard deviations of costs during the $(j+1)^{th}, j^{th}$ months, and

r_j = serial correlation coefficient between costs in $(j+1)^{th}$ and j^{th} months.

To apply the above model to generate monthly costs at a desalination plant, monthly mean, standard deviation and serial correlation coefficient are necessary. These statistical measurements are obtained from analysis of monthly historical costs.

To run the model, the cost in the first month C_1 will be the average costs of January months in the historical data C^*_{JAN}. Subsequent monthly costs are then as per the Thomas-Fiering seasonal model, as follows:

$$C_2 = C^*_{FEB} + b_{FEB/JAN}\left(C_1 - C^*_{JAN}\right) + t_1 S_{FEB}\sqrt{(1 - r^2_{FEB/JAN})} \qquad (3\text{-}19)$$

$$C_3 = C^*_{MAR} + b_{MAR/FEB}(C_2 - C^*_{FEB}) + t_2 S_{MAR}\sqrt{(1 - r^2_{MAR/FEB})} \qquad (3\text{-}20)$$

$$\Big\downarrow$$

$$C_{13} = C^*_{JAN} + b_{JAN/DEC}(C_{12} - C^*_{DEC}) + t_{12} S_{JAN}\sqrt{(1 - r^2_{JAN/DEC})} \qquad (3\text{-}21)$$

$$\Big\downarrow$$

And so on, until one run is complete, $i.e. C_{120}$

$$C_{120} = C^*_{DEC} + b_{DEC/NOV}(C_{119} - C^*_{NOV}) + t_{119} S_{DEC}\sqrt{(1 - r^2_{DEC/NOV})} \qquad (3\text{-}22)$$

3.4.3. Confidence Intervals

Using the replicated stochastic data, 100 stochastic models of TWP and TUC will be developed. To find the 95% confidence interval limits of these replicates, the parameters of the 100 stochastic model equations had to be determined. So, the parameters of the final model equation were the mean of these parameters (constant and slope). Similarly, the 95 % confidence limits of the model parameters can also be found using (Diciccio & Efron, 1996; Motulsky & Christopoulos, 2003):

$$95\%\ CI\ of\ the\ constant = \mu_c \mp 1.95\ \sigma_c \tag{3-23}$$

$$95\%\ CI\ of\ the\ slope = \mu_s \mp 1.95\ \sigma_s \tag{3-24}$$

where μ_c is the mean and σ_c is the standard deviation of the constant parameters of 100 stochastic models, while μ_s is the mean and σ_s is the standard deviation of the slope parameters of the 100 stochastic models.

3.5. Summary

This chapter described the methodology applied to develop predictive models of the cost of water produce by seawater desalination plants in Saudi Arabia. At the beginning of the chapter, there was a brief description of the plants for which the data had been collected.

In all, there were 16 desalination plants with data available between the years 2001 and 2010. The collected data gave a total of 1920 monthly data points. The collected data include monthly total water production, type of desalination technique, monthly average of sea water salinity, monthly average of product water salinity, monthly energy consumption per cubic meter of water production, and monthly total cost per cubic meter of water production. A description was presented of the major features of the collected data. This chapter also described the Monte Carlo simulation approach that will be used to construct the uncertainty bounds of the cost prediction model of desalted water. The Monte Carlo approach involved replicating the historical data 100 times, using the Thomas- Fiering time series model.

Chapter 4 - Annual Capital Cost Estimation

4.1. Introduction

Economic evaluation involves evaluation over a period of time and must take account of the time value of money. This is because the value of money is affected by inflation, which is the decline in the purchasing power of money, and the opportunity cost of capital, which is the rate of return available on the best alternative investment (Kelly & Male, 1993).

The time value of the capital cost of the desalination plants included in the existing research must be evaluated to reach its annualised value. These plants are public projects owned by the Saudi Arabian government, the pertinent issues are therefore establishing the most suitable method for evaluating the annual capital cost in such public projects, and the appropriate rate of return that can be used, given their life cycle of 30 years.

To estimate the annual capital cost of desalination plants, the methodology involves two stages. The first stage is data collection, which includes capital costs and the characteristics of the desalination plants, as discussed in section 3.1.1. The second stage is the estimation of the annual capital cost, which requires us to know three things: the correct method of financial estimation, the interest rate, and the salvage value of the desalination plant and how it can be used. These issues are discussed in the following sections.

4.2. Estimation of Annual Capital Cost

The capital cost of any investment is accrued during the first year of the life cycle as discussed in section 2.4.1 (Schade, 2007). Therefore the estimation of the annual capital costs of the desalination plants included in current research will be assumed as an investment evaluated in first year of its lifecycle.

As mentioned previously in Chapter 2, different accounting methods have been used to evaluate annual capital costs, including payback period (BP), discounted payback period (DPB), net present value (NPV), internal rate of return (IRR), and equivalent annual cost (EAC) (Brigham & Ehrhardt, 2005; Sullivn, Wicks, & Luxhoj, 2003). All these methods depend on profit and expected cash flow from the proposed project. However, because the desalination plants in KSA are public sector projects, the current research will focus on cost rather than on the usual practice of cash flow. Consequently, the equivalent annual cost (EAC) method is a suitable method to account for annual capital costs in such situations (TFSA, 2013) and where there are different desalination plants with different start times (Kishk et al., 2003; Schade, 2007). . EAC is also often called ‘amortised annual capital cost’ (Zhou & Tol, 2005). EAC uses Equation 2-4 which is reproduced here:

$$EAC = NPV * \frac{r(1+r)^n}{(1+r)^n - 1}$$

Once EAC is known, the equivalent monthly capital cost can be obtained using

$$EMC = \frac{EAC}{12} \tag{4-1}$$

where EAC is the equivalent annual cost at beginning of project, NPV is the net present value, which is total construction cost minus present salvage value (section 2.4.1), *EMC* is the equivalent monthly capital cost, n is the life cycle (i.e. useful years), which has been assumed to be 30 years, so matching with actual life cycles and those used in previous studies (Raluy, Serra, Uche, & Valero, 2004; Zhou & Tol, 2005), and r is the rate of return or discount rate (CDC, 2013; Kishk et al., 2003).

The final total monthly costs in each plant in the current study will be calculated by the following equation (Kishk at al., 2003):

$$Total\ monthly\ costs = EMC + total\ monthly\ operation\ costs \quad (4\text{-}2)$$

4.2.1. Estimating the Rate of Return (r)

Desalination plants in Saudi Arabia are public projects paid for by the Saudi government. This means that the rate of return (r) to be applied is equal to the yield of the long term bonds of the Saudi Arabian government (DER, 1991; Musgrave & Musgrave, 1989; Sharp & Olson., 1978). However, the Saudi government development bonds are, in practice, directly linked to the returns on US treasury bonds (Al-Basam, 2007; Wilson, 2007). Consequently, the yield of long-term United States bonds was applied in this study. As the life cycle of a plant is 30 years, the market yield percentage on U.S. Treasury securities in a 30-year investment has been used in this research (Figure 4-1) (BGFRS, 2012; Demiralp & Yılmaz, 2012; InvestmentTools, 2013; Parks & President, 2002; USDT, 2012).

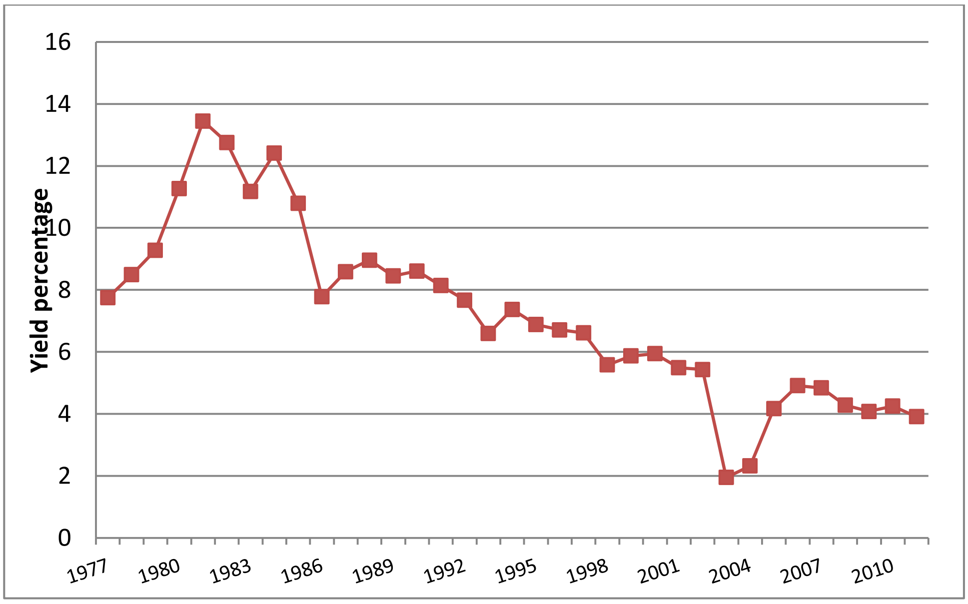

Figure 4-1: Market yield percentage on U.S. Treasury securities at 30-year investment.

4.2.2. Estimate of Salvage Value

The salvage value is the residual, or market, value for the project assets at the end of its life cycle. In many economics, evaluations have often assumed no salvage value (Agashichev, 2004; Rogers et al, 2008), while others compute it as 5% of the capital cost (Al-Qahtani & Elkamel, 2009; Kannan et al., 2004). Furthermore, a number of private studies in desalination economics place salvage value at 10% of the capital cost (Frioui & Oumeddour, 2008; Rasmala, 2011). However, in the current research, the salvage value will be assumed at 5% of the capital cost, which is close to the actual salvage value of the Jeddah 2 plant at the end of its life in 2008, this being 15 million Saudi Riyals. The present value of the salvage value (PSV) then becomes (Agashichev, 2004; Brigham & Ehrhardt, 2005; DER, 1991):

$$PSV = \frac{Salvage\ value}{(1+r)^{n}} = \frac{0.05\ C}{(1+r)^{30}} \quad (4\text{-}3)$$

Where, n = 30 years and C is the capital cost.

4.3. Results and Discussion

The annual capital cost of seawater desalination plants has been estimated based on the opportunity cost value (EAC), which depends on the rate of return of the investment and the life cycle and the results are shown in Table 4-1. A 30 year life cycle was assumed for all plants, apart from Jeddah-2, which was closed in 2008 after 29 years’ service. The market yield percentages used have been based on the historical recorded of market yield percentages in first year of the life cycle of a plant rather taking the average market yield to calculate the actual capital cost of each desalination plant. The historical yields were presented earlier in Figure 4-1, from which the prevailing yields at the year of commissioning of each plant were extracted. These yields are shown in Figure 4-

2 and vary between a maximum of 13.5% at the Yanbu-1 plant to a minimum of 5.5% at the Shuiba 2 plant.

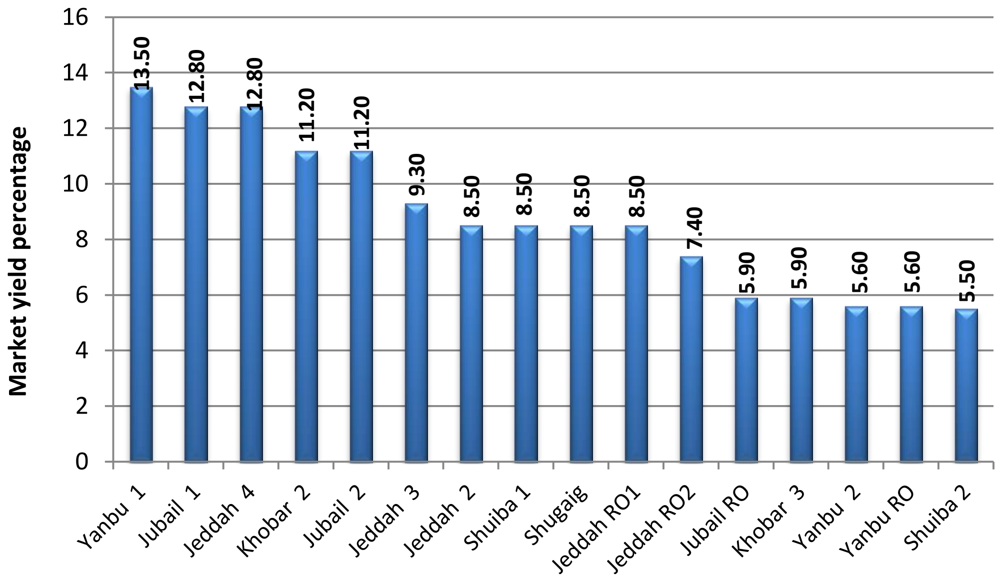

Figure 4-2: Applicable r value for desalination plants in Saudi Arabia based on the year of plant commission.

As a result of applying the rate of return in the current research capital cost, there is a considerable change in the salvage value, as well as in annual capital cost (Figure 4-4). The salvage value of desalination plants is inversely proportional to the rate of return, due to fact that the salvage value will decrease when the present salvage value is calculated (see Equation 4-3). For example, the salvage value of the Jeddah-2 plant was 15 million Saudi Riyals at the end of the plant's life cycle in 2008. However, the present salvage value (PSV) at the beginning of the plant life cycle in 1978 will be around 1.4 million Saudi Riyals at a rate of return of 8.5%, as shown in Figure 4-3.

Alterations in annual capital cost are directly proportional to the rate of return: for example, the capital costs of the Yanbu-1 plant and Yanbu-RO plant were 651.4 and 878 million Saudi Riyals, with the rate of return being 13.5% and 5.6% respectively. This significant difference in the rate of return makes the annual capital cost of Yanbu-1 higher than that of Yanbu-RO by 2.5 million Saudi Riyals, even though Yanbu-RO had a higher capital cost (see Figure 4-4, Table 4-1). Incidentally, the equivalent annual capital cost on average, maximum, and minimum of r values of the plants in current study have been calculated as mentioned in Appendix H.

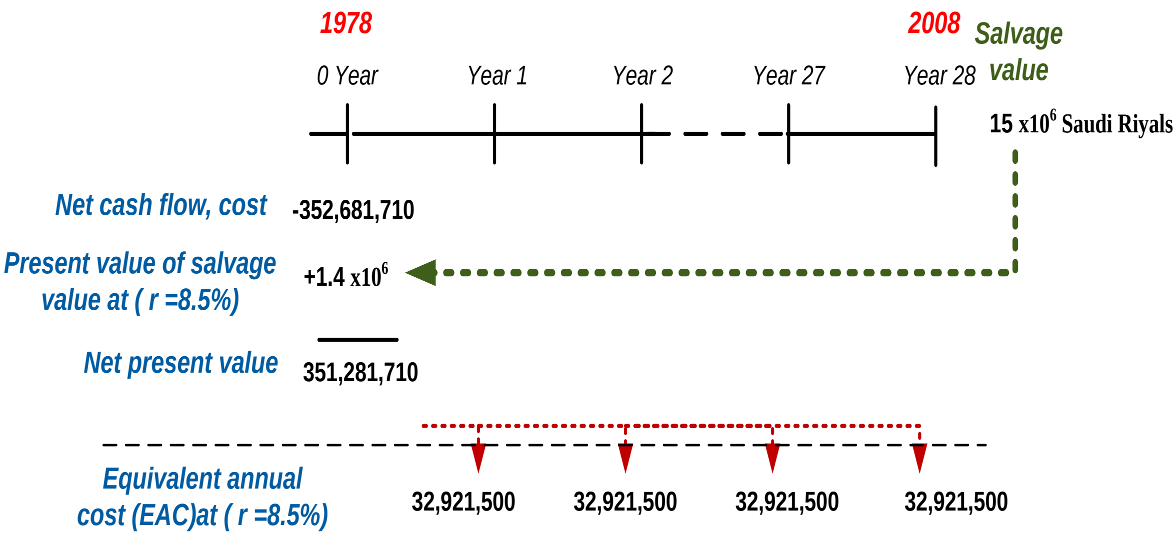

Figure 4-3: EAC calculation mechanism in the Jeddah 2 desalination plant**.**

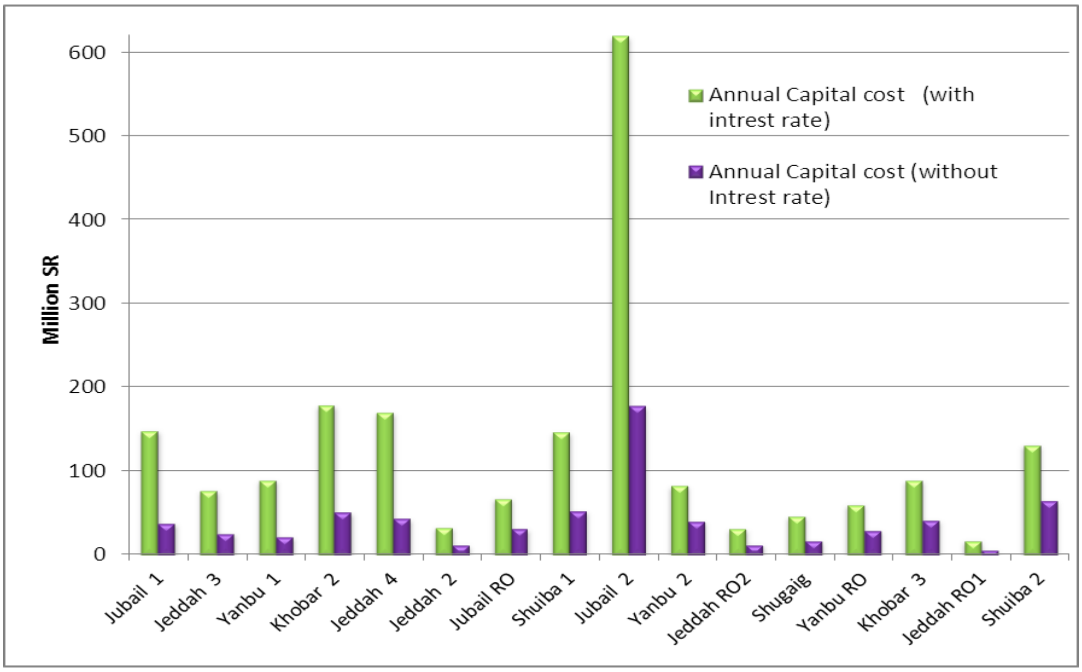

Figure 4-4: Comparison of the annual capital cost of desalination plants with and without rate of return.

The nominal capital cost of one cubic metre of production can also be estimated and this is shown in Figure 4-5. As was the case in the annual cost, there is a considerable change in unit production cost when time value of money was considered as opposed to when it was ignored. Although the annual unit capital cost more than doubles in the majority of desalination plants, it has tripled in plants such as Yanbu-1 and Jeddah-4, where it jumped from 0.55, 05 SR/ m^3 to 2.27, 2.1 SR/ m^3 respectively. As can be seen from Figure 4-5, the highest unit capital cost is for Jubail-1 at 2.96 SR/ m^3, while the lowest is Shuiba-2, at 0.79 SR/ m^3.

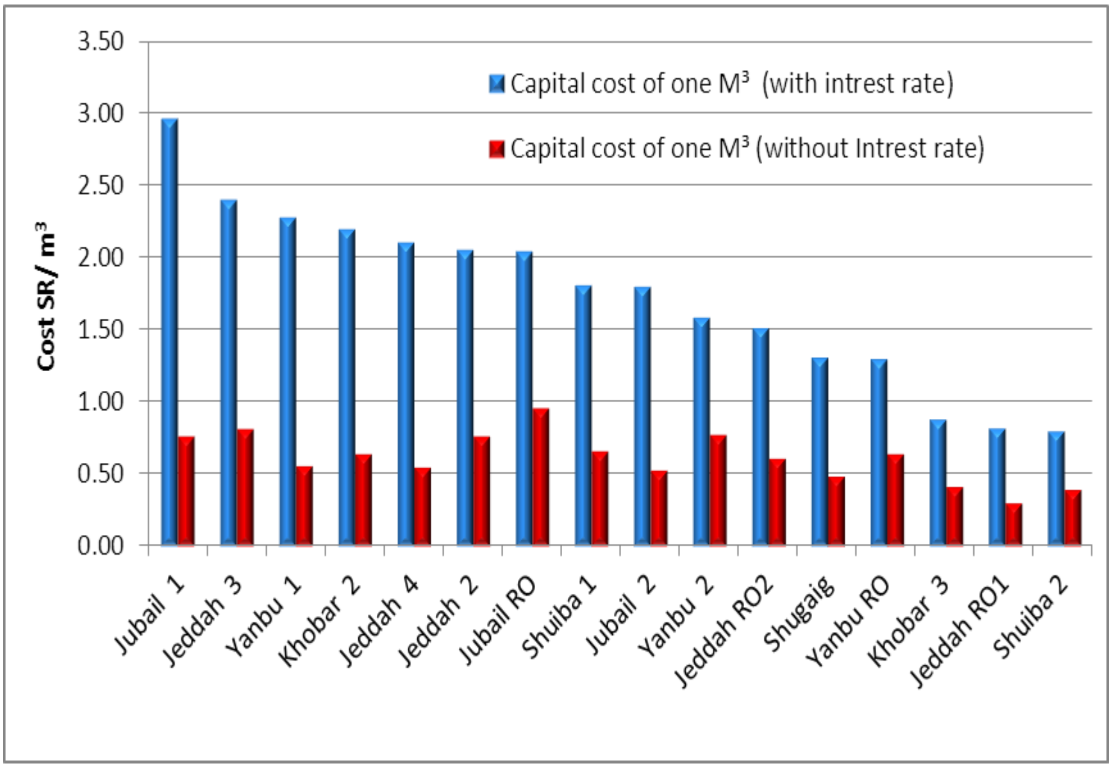

Figure 4-5: Comparison capital costs of one m³ of water production from desalination plants based on installed capacity, with and without rate of return.

Table 4-1: Results of equivalent annual cost calculation (the life cycle of plants is 30 years).

Plant	Capital cost, SR (Saudi Riyals)	Yield on U.S. treasury bonds (r)	Life cycle (years)	Present value of Salvage value (*PSV*)*	Annuity factor (A)	Equivalent annual cost, *EAC* (Riyals)	Equivalent monthly capital cost, *EMC* SR
Jubail 1	1,135,734,000.00	0.128	30	1,547,371.60	7.62	148,776,192.10	12,398,016.00
Jubail 2	5,325,488,100.00	0.112	30	11,079,733.90	8.57	619,946,979.40	51,662,248.30
Jubail RO	945,964,543.75	0.059	30	8,376,176.20	13.85	67,678,044.50	5,639,837.00
Khobar 2	1,535,564,400.00	0.112	30	3,194,757.90	8.57	178,757,044.20	14,896,420.30
Khobar 3	1,245,049,800.00	0.059	30	11,024,468.70	13.85	89,075,786.50	7,422,982.20
Jeddah 2	352,681,710.00	0.085	29	1,411,853.70	10.67	32,921,500.20	2,743,458.40
Jeddah 3	778,115,592.75	0.093	30	2,715,148.20	10.02	77,355,640.00	6,446,303.30
Jeddah 4	1,299,364,806.50	0.128	30	1,770,309.00	7.62	170,211,112.90	14,184,259.40
Jeddah RO - 1	183,537,186.54	0.085	30	805,021.30	10.8	16,925,634.90	1,410,469.60
Jeddah RO - 2	375,287,058.21	0.074	30	2,222,516.50	11.96	31,188,991.50	2,599,082.60
Yanbu 1	651,407,481.05	0.135	30	739,073.70	7.27	89,546,861.80	7,462,238.50
Yanbu 2	1,204,120,069.00	0.056	30	11,808,373.20	14.41	82,763,663.20	6,896,971.90
Yanbu RO	878,040,820.75	0.056	30	8,610,631.10	14.41	60,351,020.30	5,029,251.70
Shuiba 1	1,589,418,572.50	0.085	30	6,971,425.60	10.8	146,574,756.30	12,214,563.00
Shuiba 2	1,931,801,599.29	0.055	30	19,435,412.20	14.55	131,435,814.50	10,952,984.50
Shugaig	501,140,080.96	0.085	30	2,198,074.70	10.8	46,214,689.20	3,851,224.10

4.4. Summary

The annual capital cost of seawater desalination plants has been estimated based on the opportunity cost value, which is dependent on rate of return of invested money. The equivalent annual cost (EAC) method is suitable to account for the annual capital cost in situations where there are different desalination plants with different start times, as well as to evaluate non-profit projects. As the desalination plants in the current research are public projects with a 30 year life cycle, the rate of return applied in order to calculate EAC is the yield percentage at the U.S. treasury at 30 years investment in the first year of the life cycle of each plant included in the current study.

The salvage value has been accounted for at 5% of the capital cost, guided by the salvage value at the recently de-commissioned Jeddah 2 plant. As a result of applying the rate of return, the salvage values decrease when the present value is calculated in first year of the life cycle of each plant. On the other hand, the change in the annual capital cost is directly proportional to the rate of return. In conclusion, differences in the rate of return make a difference in the annual capital cost, which is reflected in the estimation of the capital costs of one cubic metre of production. With an increase in rate of return, the unit capital cost will increase and vice versa.

Chapter 5 - Monthly Operating Cost Estimation and Infilling

5.1. Introduction

As noted early in Chapter 3, although annual operating cost data are complete for the period 2001-2010 at all the desalination plants, the monthly cost data contain gaps. Given the relative shortness of the available data for model development, it is not reasonable to ignore these missing values because that will reduce the data record length further, resulting in less accuracy of the calibrated model. Thus, a method of infilling the missing monthly data record is needed to provide a complete record for the monthly cost prediction model.

The infilling was achieved by disaggregating the available annual data using the method of fragments. Method of fragments is widely used in stochastic hydrology studies and as recently investigated by Silva and Portela (2012), the overriding consideration is how to define and select the fragments (McMahon & Mein, 1986; McMahon & Adeloye, 2005). Three approaches of the method of fragments were used to define the classes and selection of the fragments (Silva & Portela, 2012). This chapter will summarise the data, present the results of its applications and validate the final results by comparing the different approaches.

5.2. Monthly Operating Cost Allocation in Seawater Desalination Plants in Saudi Arabia

As mentioned in section 2.4, the costs of water production from desalination plants comprise capital and operating costs. The operating costs of seawater desalination plants in Saudi Arabia include the operational, maintenance and administrative costs. Operational costs pertain to fuel, chemicals and operational staff, whilst maintenance costs are related to spare parts and to both contracted and maintenance staff (SWCC, 2010). These different costs are not available in the current study, although the study would be more comprehensive if these data available.

The allocation of the monthly operation costs of water production from the total annual cost depends on the schedules of maintenance, which in turn mostly depend on water demand. During the annual maintenance schedule time, there would be an increase in labour and spare parts costs; whereas there would be a decline in costs of fuel and chemicals, due to stopping of some of the production units.

In Gulf countries such as Saudi Arabia, the highest water demand occurs in the summer season (June to August); consequently, the winter season (December-February) is the best time for maintenance work, since the water demand is generally low at this time period (Hamoda, 2001; Ludwig, 2004). The monthly cost data shown in Figure 5-1 reflect this pattern in most of the desalination plants. For example, in December, the average unit cost of water production is high in all the plants except Jubail 1, due to maintenance costs and the decline of total production. On the other hand, in the summer season, most of the plants have a lower unit cost of water production, due to lower maintenance costs and more water production.

These recurring scheduled events provide a good indication that the percentage of the monthly cost to the total annual cost is almost repeated exactly, year after year. So, this phenomena can be used as a method of fragments to detect the monthly production costs, if the total annual costs of that year and the historical data of monthly costs for some other years are available.

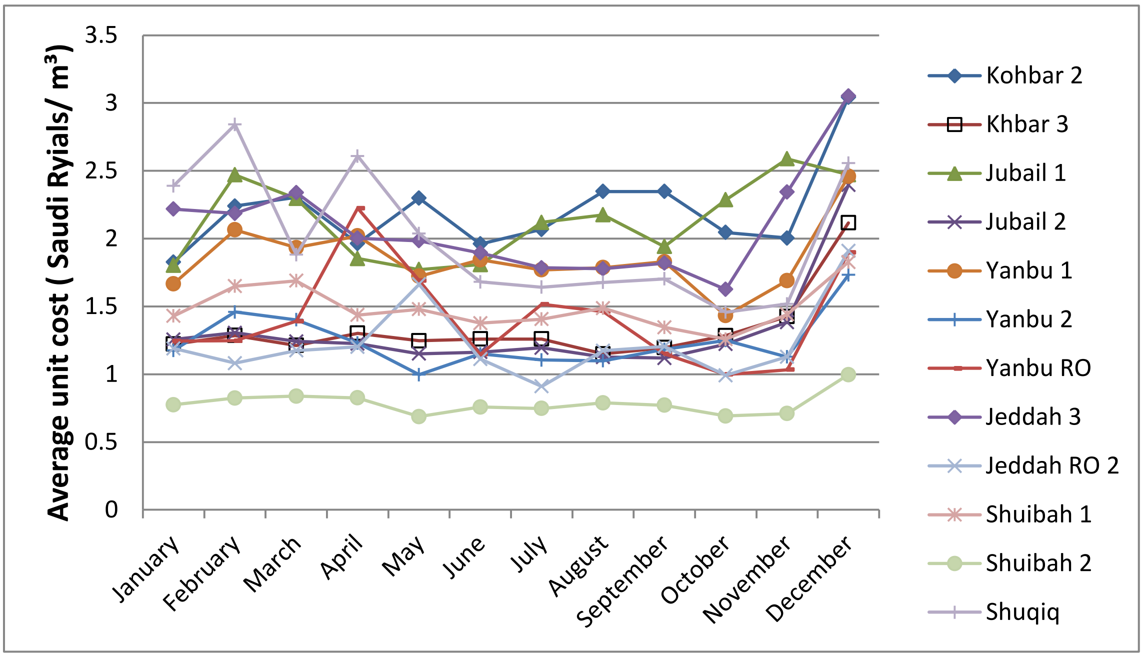

Figure 5-1: Variation of the average of monthly unit costs of seawater desalination plants in Saudi Arabia (2005-2008).

5.3. Method of Fragments

The method of fragments (MOF) was first proposed by Svanidze in 1964 as a way of disaggregating of annual runoff data into monthly data by selecting the appropriate fragment from the historical data. In this method, for a given set of historical data, a new monthly time series is formed by dividing each monthly value by the corresponding annual value and each year is referred to as one set of fragments (McMahon & Adeloye, 2005; McMahon & Mein, 1986).

The fragments of historical monthly data from annual data were estimated using equation 5-1.

$$Fc_{j,i} = c_{j,i} \,/\, C_i \tag{5-1}$$

i = 1, 2, ..., N; j =1, 2,....., 12

where $c_{j,i}$ is the historical monthly cost for month j, year i, and C_i is the total annual cost in year i and $Fc_{j,i}$ are referred to as the fragments of month j, year i.

After estimating the fragments using the available, complete historical annual monthly data, these fragments will then form the basis for disaggregating the annual costs that do not have monthly costs. However, an important aspect in the method of fragments is the way of selecting the appropriate fragment to apply to each of the annual value that is to be disaggregated (Silva & Portela, 2012). There are three approaches which can be used to select the correct fragments which are now explained.

5.3.1. First Approach

The simplest way of fragment selection was proposed by Svanidze in 1964. In this approach, there is one class of annual readings from 0 to infinity (∞). Fragments are formed using Equation 5-1 and are numbered from 1to N. The selection of fragments is done randomly without replacement as follows: for each annual data to be disaggregated, a random number is generated using the uniform distribution between (1, N) where, N is the number of years of complete historical record. The fragment whose number is the same as the random is then selected for the disaggregation. Once the first annual data has been disaggregated, another random number is generated and the process repeated until all the annual values have been disaggregated. Since the random operation is without replacement, if a random number generated is the same as any of those previously generated and used, it must be discarded and a new one generated. This requirement means that the number of historical annual data with accompanying monthly data must be equal to or more than the number of annual data without monthly data, which need to be disaggregated (Silva & Portela, 2012).

5.3.2. Second Approach.

This is based on the relationship between the fragments that have been selected and the annual value. Thus, unlike the random approach which uses fragments unrelated to the annual value being disaggregated, the second approach uses a fragment of a historical year that has a close annual value will be used (R. Srikanthan & McMahon, 1982). This is carried out as follows (McMahon & Adeloye, 2005):

(i) Find the fragments for each year using Equation 5-1.

(ii) Rank the historical annual cost from the lowest value to the highest value i.e. $C_1 \leq C_2 \leq C_3 \ldots \leq C_N$

where C_1 is the lowest value and C_N is the highest value. Carry the fragments along with the ranked annual cost.

(iii) Define upper and lower limits for each class (Rank) of the historical data. For example, C_1, the lower limit is zero and the upper limit will be (($C_1 + C_2$)/ 2). In contrast, there is no upper limit (∞) for class N.

(iv) Assign fragments to the classes defined. Those fragments that are related with the smallest annual value, C_1, are assigned to historical class 1. Those related with the second largest annual value, C_2, are assigned to historical class 2, and so forth.

(v) Select an annual cost that does not have monthly values and check which of the historical class intervals it belongs to in (iv) above, and hence use the fragment associated with that historical class to disaggregate the annual cost to monthly values.

5.3.3. Third Approach.

In this approach, the classes of the fragments of annual values are defined by probability intervals, with an increment of 10% between classes. Silva and Portela developed this approach in 2012 and they compared it with the other two approaches (first and second). At the outcome of this comparison, they concluded that the third approach disaggregated annual value to monthly value more accurately (Silva & Portela, 2012; Silva, 2010). The steps involved in this approach are as follows:

(i) Estimate the new cost probability limits of the classes' ranking by applying the 3-parameter log-normal distribution using equation (5-2) (Adeloye et al., 2010).

$$c_i^* = \partial + \exp(\mu + z_p * \sigma) \tag{5-2}$$

where: c_i^* is the new annual cost limit of the historical data,

∂ is the lower limit, which can be calculated by the equation (4-3):

$$\partial = \frac{(c_{max} * c_{min}) - c_{mid}^2}{c_{max} + c_{min} - c_{mid}^2} \tag{5-3}$$

where c_{max} , c_{min}, c_{mid} are the maximum, minimum, and median of the observed annual cost, respectively.

μ, and σ are the mean and standard deviation of the 3-parameter log-normal distribution of the observed annual cost:

$$\mu = \frac{1}{n} \sum_{i=1}^{n} y_i \tag{5-4}$$

$$\sigma = \sqrt{\frac{1}{n-1} \sum_{i=1}^{n} (y_i - \mu)^2} \tag{5-5}$$

$$y_i = \ln(c_i - \partial) \tag{5-6}$$

$$i = 1,2 \ldots\ldots, n$$

z_p is the normally distributed random variable with a mean of 0 and standard deviation of 1(Standard normal distribution), which can be calculated by using equation (5-7) at non-exceedance probability intervals (P in %) (Adeloye et al., 2010; Stedinger et al., 1993) with an increment of 10%, (i.e. 10%, 20%,......90%) or from standard normal distribution Tables (Field, 2013).

$$z_p = \frac{(0.01\text{P})^{0.135} - (1-0.01\text{P})^{0.135}}{0.1975} \tag{5-7}$$

To find the new probability cost (c_i^*) limit, take the exponential of the logarithms of annual cost at non-exceedance probability intervals (P %) and add the lower limit using the equation (5-2).

(ii) The new annual cost limits will be in ten probable classes' limits which have the same chance. The first limit from zero to the new annual cost, at 10% probability intervals and so on. The last limit (tenth) will be from the new annual cost 90% probability interval to infinity (∞), since there is no upper limit.

(iii) Assign fragments to the classes defined. In our case, assign the annual cost for the years 2005, 2006, 2007 and 2008 to the class limit defined.

(iv) If there are empty classes, these need to be redefined. In the case that the first class is empty, redefine it by including it in the next class. In the case that the last class is empty, redefine it by including it in the preceding class. In the case that an intermediate class is empty, redefine it by calculating the average of the probability limits of that empty class and including that in the next classes. For example, suppose the original classes are $[c_{n-1}^*, c_n^*]$, $[c_n^*, c_{n+1}^*]$, $[c_{n+1}^*, c_{n+2}^*]$ and $[c_n^*, c_{n+1}^*]$ is an empty class. The new classes will be $[c_{n-1}^*, c_\partial^*]$, $[c_\partial^*, c_{n+2}^*]$, where c_∂^* is the average of c_n^*, c_{n+1}^* limits and so on, until all the empty classes are filled.

(v) Select an annual cost and check for which of the class intervals it belongs to in (iii) above, and hence use the fragment associated with that class to disaggregate the annual cost to monthly values. If there is more than one fragment in one class, the fragment is randomly selected. If any class runs out of fragments, refill with the relevant fragment.

5.4. Fragments of the observed monthly operating cost

The operating cost is a part of the total cost of water production from sea water desalination plants (section 2.4.2), which is the dependent variable that has been studied in this research. The operating costs collected were for the years between 2001-2010, but while the data for 2005-2008 included monthly costs, only the annual costs were available for two intervals in the data: 2001-2004 and 2009-2010, see section 3.4.1.

This study thus applied method of fragments to reconstruct the monthly operation cost of water production from seawater desalination plants so as to provide a complete record for 2001 to 2010. For each plant, four steps were carried out: fragmenting of the observed monthly operation cost; class ranking, together with identifying class limits; generating the missing monthly costs and validation of the generated values. However, as the Shuqiq seawater desalination plant was used as an example for applying the method of fragments to generate monthly costs of water production, only its details will be presented here. For the other plants, the results of method of fragments are presented in Appendix B. The fragments for the Shuqiq plant are shown in Table 5-1 and were obtained using Equation 5-1.

Table 5-1: The fragments for the observed monthly operating cost of the Shuqiq plant (Saudi Riyals).

Year	**2005**		**2006**		**2007**		**2008**	
Annual cost	***76,194,705.82***		***68096169.79***		***66946315.51***		***77466573.22***	
	Monthly cost	**Fragment**	**Monthly cost**	**Fragment**	**Monthly cost**	**Fragment**	**Monthly cost**	**Fragment**
Jan	6,644,692.89	0.087207	7,426,966.52	0.109066	5,596,074.44	0.08359	5,197,506.68	0.067094
Feb	5,360,143.81	0.070348	6,466,061.92	0.094955	5,099,275.80	0.07617	5,444,424.97	0.070281
Mar	7,237,571.13	0.094988	7,433,756.58	0.109166	4,989,669.90	0.074532	5,541,821.86	0.071538
Apr	6,905,126.31	0.090625	6,617,979.19	0.097186	5,500,398.40	0.082161	14,266,208.01	0.18416
May	6,441,921.43	0.084546	5,493,954.26	0.080679	5,061,702.85	0.075608	9,026,650.58	0.116523
Jun	6,196,770.52	0.081328	5,122,602.40	0.075226	5,103,170.44	0.076228	4,978,935.33	0.064272
Jul	6,412,235.60	0.084156	5,067,000.29	0.074409	5,271,782.51	0.078746	4,924,576.52	0.06357
Aug	6,537,948.08	0.085806	5,413,566.72	0.079499	5,268,014.58	0.07869	5,171,583.69	0.066759
Sep	6,308,453.28	0.082794	5,300,040.04	0.077832	5,285,315.18	0.078949	4,947,040.95	0.06386
Oct	5,865,019.36	0.076974	3,887,846.90	0.057093	4,957,570.04	0.074053	4,676,609.75	0.060369
Nov	5,587,151.76	0.073327	3,588,808.44	0.052702	4,725,922.99	0.070593	5,417,524.30	0.069934
Dec	6,697,671.62	0.087902	6,277,586.53	0.092187	10,087,418.38	0.150679	7,873,690.59	0.10164

5.4.1. First Approach to Disaggregation

As mentioned above, in this approach, the number of historical annual data that include historical monthly data must be equal to or more than the number of years that do not have monthly data. This approach cannot, therefore, be applied here, because there are only 4 years (2005-2008) of complete historical records whereas 6 years of annual cost data would need to be disaggregated to monthly costs.

5.4.2. Second Approach to Disaggregation

The annual historical costs were ranked and the monthly values are shown from the lowest to the highest in Table 5-2. As mentioned earlier, in section 5.3.2, the lowest limit for class 1 in this ranking is zero and the upper limit for class 4 is infinity (∞).The limit between class 1 and 2 was the average annual production of the years 2007 and 2006, and so forth, for other class limits.

Table 5-2: Class ranking with class limits for the Shuqiq plant

Class ranking	Year	Annual cost (SR)	Class limits (SR)
			0
1	2007	66,946,315.51	
			67,521,242.65
2	2006	68,096,169.79	
			72,145,437.80
3	2005	76,194,705.82	
			76,830,639.52
4	2008	77,466,573.23	
			∞

The fragments for each of these classes are reported in Table 5-1. To disaggregate any annual cost, its value is first examined to see its appropriate class in Table 5-2. For example, to generate the monthly costs for the Shuqiq plant for the year 2001, the total annual cost was 73,084,694.70 Saudi Riyals

(SR). With reference to the class ranking table (Table 5-2), this value falls between "72,145,437.80" and "76,830,639.52", i.e. class 3) which means the fragment of year 2005 (see Table 5-1) will be used to generate the monthly costs of 2001 for the Shuqiq plant. The same steps were applied to create monthly costs for the Shuqiq sea water desalination plant for years 2002, 2003, 2004, 2009 and 2010.

The above steps were applied to all the fifteen remaining seawater desalination plants selected for this study, to generate monthly costs for the years where the monthly costs are missing, based on second approach of class ranking.

5.4.3. Third Approach

Estimate the new annual cost limits of class ranking by applying the 3-parameters log-normal distribution which are ∂,μ and σ as mentioned in section 5.3.3. The probability estimation must be the non-exceedance probability of the annual cost, with an increment of 10%, as shown in Table 5-3. After that, fragments are assigned to the classes defined, redefining the empty classes, as mentioned in Table 5-4. For example "Shuqiq Plant", annual costs become two classes after redefining the empty classes, (i.e. class 1: 0 to 72247269.24 and, class 2: 72247269.24 to infinity (∞)). Finally, the annual costs of the years 2000-2004 and 2009-2010 were disaggregated to monthly values

Table 5-3: Estimation of the new probability cost limits of the Shuqiq plant by using the third approach class ranking**.**

Year	Annual historical cost (c_i), SR	$y_i = \ln(c_i - \partial)$	Probability intervals %	Standard normal distribution z_P	New probability cost (C_i^*) limit =Exp($\mu + z_P * \sigma$)+ ∂, SR
2000	71,282,507.38	18.08	10%	-1.28155	63,537,783.74
2001	73,084,694.70	18.11	20%	-0.84162	66,392,699.45
2002	74,367,129.53	18.12	30%	-0.5244	68,530,561.13
2003	59,266,619.97	17.90	40%	-0.25335	70,411,721.7
2004	65,701,281.46	18.00	50%	0	72,216,701.59
2005	76,194,705.82	18.24	60%	0.25335	74,067,951.51
2006	68,096,169.79	18.09	70%	0.5244	76,101,113.18
2007	66,946,315.51	18.02	80%	0.84162	78,551,588.24
2008	77,466,573.23	18.17	90%	1.28155	82,081,112.72
2009	83,171,675.09	18.24			
2010	71,750,328.73	18.09			
Lower limit (∂) 0.042502129		Mean (μ) = 18.10			
		S.D (σ) = 0.099907608			

Table 5-4: Assignation of fragments to the classes defined and redefining empty classes, using third approach class ranking.

Classes	New probability cost (c_i) class limit	Observed Year (monthly fragment available) allocation	Final Limits of the classes
0	0		0
C1	63,537,783.74		↑
C2	66,392,699.45		
		68,096,169.79 (***2006***), 66,946,315.51 (***2007***)	
C3	68,530,561.13		
C4	70,411,721.7		↓
C5	72,216,701.59		72,247,269.24
C6	74,067,951.51		↑
C7	76,101,113.18		
		76,194,705.81 (***2005***), 77,466,573.22 (***2008***)	
C8	78,551,588.24		
C9	82,081,112.72		↓
∞	**∞**		**∞**

5.5. Results and Discussion

The method of fragments has been used to disaggregate the annual cost into monthly costs. Out of three approaches used previously in selecting the appropriate fragmentation from historical data, two approaches have been used in the current research. Both approaches have given a good indication that the method of fragments is highly suitable for the disaggregation of the annual operation cost of water production from seawater desalination plants to monthly costs. As can be seen in Appendices B1 and B2 for approaches 2 and 3 respectively, different results are obtained between the two approaches in most of the plants, except Jubail 2, Khobar 2, Kohbar 3, Jeddah 2, and Jeddah 4, which have the same results for both approaches. This is due to the limitation of the available historical monthly cost (2005-2008), which leads to few classes for ranking. Therefore, the new fragments of the monthly cost for some years were the same. For example, the fragmentation of 2001 and 2004 at the Shuqiq plant both used the same fragments of the year 2006, in approaches 2 and 3, as shown in Tables 5-5 and 5-6 respectively.

Both approaches have been compared with historical data, to validate them as well as to select one of them to apply in the current research. The validation is described in the following sub-section.

Table 5-5: Disaggregation of annual operating cost into monthly operating costs of the Shuqiq plant by using 2nd approach class ranking (Saudi Riyals).

Year	2000	2001	2002	2003	2004	2009	2010
Annual cost	**71,282,507.38**	**73,084,694.70**	**74,367,129.53**	**59,266,619.97**	**65,701,281.46**	**83,171,675.09**	**71,750,328.73**
Jan	7,774,487.1	6,373,478.9	6,485,315.9	4,954,125.0	5,492,001.5	5,580,282.2	7,825,510.5
Feb	6,768,620.1	5,141,360.8	5,231,577.5	4,514,316.3	5,004,442.0	5,845,385.0	6,813,042.1
Mar	7,781,594.9	6,942,157.9	7,063,973.6	4,417,283.7	4,896,874.5	5,949,954.8	7,832,664.9
Apr	6,927,645.9	6,623,282.3	6,739,502.7	4,869,424.4	5,398,104.8	15,316,856.9	6,973,111.5
May	5,751,025.9	6,178,983.9	6,287,408.0	4,481,053.5	4,967,567.8	9,691,427.1	5,788,769.4
Jun	5,362,297.8	5,943,839.2	6,048,137.2	4,517,764.1	5,008,264.2	5,345,613.9	5,397,490.2
Jul	5,304,094.0	6,150,509.8	6,258,434.2	4,667,034.0	5,173,740.5	5,287,251.8	5,338,904.3
Aug	5,666,876.9	6,271,091.1	6,381,131.4	4,663,698.3	5,170,042.7	5,552,450.1	5,704,068.1
Sep	5,548,038.1	6,050,963.5	6,157,141.2	4,679,014.3	5,187,021.5	5,311,370.6	5,584,449.4
Oct	4,069,766.0	5,625,629.0	5,724,343.3	4,388,866.2	4,865,371.6	5,021,023.3	4,096,475.5
Nov	3,756,735.0	5,359,103.1	5,453,140.5	4,183,792.3	4,638,032.6	5,816,503.2	3,781,390.2
Dec	6,571,325.7	6,424,295.2	6,537,023.9	8,930,247.9	9,899,817.6	8,453,556.3	6,614,452.8

Table 5-6: Disaggregation of annual operating cost into monthly operating cost of the Shuqiq plant using 3rd approach of class ranking (Saudi Riyals).

Year	2000	2001	2002	2003	2004	2009	2010
Annual cost	**71,282,507.38**	**73,084,694.70**	**74,367,129.53**	**59,266,619.97**	**65,701,281.46**	**83,171,675.09**	**71,750,328.73**
Jan	5,958,538.8	6,373,478.9	4,989,554.0	6,463,964.2	5,492,001.5	7,253,131.7	7,825,510.5
Feb	5,429,561.9	5,141,360.8	5,226,593.1	5,627,653.3	5,004,442.0	5,850,959.5	6,813,042.1
Mar	5,312,856.7	6,942,157.9	5,320,093.1	6,469,873.8	4,896,874.5	7,900,298.4	7,832,664.9
Apr	5,856,665.7	6,623,282.3	13,695,415.9	5,759,872.5	5,398,104.7	7,537,412.4	6,973,111.5
May	5,389,555.3	6,178,983.9	8,665,493.6	4,781,592.0	4,967,567.8	7,031,793.0	5,788,769.4
Jun	5,433,708.8	5,943,839.2	4,779,727.7	4,458,390.7	5,008,264.2	6,764,194.2	5,397,490.2
Jul	5,613,242.1	6,150,509.8	4,727,543.8	4,409,998.1	5,173,740.5	6,999,388.9	5,338,904.3
Aug	5,609,230.1	6,271,091.1	4,964,668.2	4,711,627.7	5,170,042.7	7,136,612.5	5,704,068.1
Sep	5,627,651.3	6,050,963.5	4,749,109.4	4,612,821.2	5,187,021.5	6,886,103.5	5,584,449.4
Oct	5,278,677.7	5,625,629.0	4,489,498.2	3,383,737.2	4,865,371.6	6,402,065.3	4,096,475.5
Nov	5,032,026.6	5,359,103.1	5,200,768.7	3,123,473.0	4,638,032.6	6,098,754.1	3,781,390.1
Dec	10,740,792.4	6,424,295.2	7,558,663.6	5,463,616.2	9,899,817.6	7,310,961.6	6,614,452.7

5.6. Performance of the disaggregation schemes

Performance of the disaggregation schemes is a step to validate the generated values. It involves a comparison of the data generated using two different approaches of the method of fragments with the historical observed values, in order to choose the best approach among the two, which suits the current study. Thus the values generated in this study were validated by comparing the mean ($\mu c_{(j,i)\ h}$) and standard deviation ($\sigma c_{(j,i)\ h}$) of monthly ratios of historical records with the mean ($\mu c_{(j,k)g}$) and standard deviation ($\sigma c_{(j,k)g}$) generated values (Mayer & Butler, 1993), where

$$\mu c_{(j,i)\ h} = \frac{1}{N_h} \sum_{i=1}^{N_h} \frac{c_{j,i}}{C_{h,i}} \qquad , j = 1, \dots, 12 \qquad (5\text{-}9)$$

$$\mu c_{(j,k)g} = \frac{1}{N_g} \sum_{k=1}^{N_g} \frac{q_{j,k}}{C_{g,k}} \qquad , j = 1, \dots, 12 \qquad (5\text{-}10)$$

$$\sigma c_{(j,i)\ h} = \sqrt{\frac{1}{N_h - 1} \sum_{i=1}^{N_h} \left(\left(\frac{c_{j,i}}{C_{h,i}}\right) - \mu c_{(j,i)h} \right)^2} \qquad , j = 1, \dots, 12 \qquad (5\text{-}11)$$

$$\sigma c_{(j,k)g} = \sqrt{\frac{1}{N_g - 1} \sum_{k=1}^{N_g} \left(\left(\frac{q_{j,k}}{C_{g,k}}\right) - \mu c_{(j,i)g} \right)^2} \qquad , j = 1, \dots, 12 \qquad (5\text{-}12)$$

where $c_{(j,i)}$ is the fragment for month *j*, year *i* of complete historic record.

$C_{h,i}$ is the annual cost for year *i* of the historic data.

$q_{j,k}$ is the fragment for month *j*, year *k* of the estimated (disaggregated) data

$C_{g,k}$ is the annual cost for year *k*

N_h is the number of years of complete monthly and annual historic data (=4 years)

N_g is the number of years of incomplete and hence disaggregated data (= 6 years)

In the current example of the Alshuqiq desalination plant, the ratios for each month (observed) were calculated by dividing the observed monthly costs by the average annual costs for those years, as shown in Table 5-7. In contrast, the ratios for the generated months were computed by dividing each generated monthly value by the average annual value of the years for which their months' values were estimated, by method of fragments, as shown in Table 5-8 for the second approach and Table 5-9 for the third approach. The average as well as the standard deviation of the ratios for each month of the year (January to December) have been estimated for both observed and generated data to get a good comparison indication, because the generated monthly values are generated based on fragments, for each month of the year. Figure 5-2 compare the means μ and standard deviations σ of the ratios of the months' values for historical and generated data (2nd and 3rd approaches) of the Shuqiq seawater desalination plant. As can be seen from Figure 5-2, the means of both approaches are very close to the historical values, except for the month of April, where both approaches slightly underestimate the value. Similarly, comparing the standard deviation of the ratios, , it is clear from Figure 5-2 that the 2nd approach is closer to historic values than the 3rd approach, in March, April, May, June, and November. In conclusion, the 2nd approach is found to be better than the 3rd approach to fragment the annual cost into monthly cost in the Alshuqiq desalination plant case study.

Table 5-7: Monthly ratios to average annual cost of the observed year that have monthly operating costs associated with the Shuqiq seawater desalination plant.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2005	0.092	0.074	0.100	0.096	0.089	0.086	0.089	0.091	0.087	0.081	0.077	0.093
2006	0.103	0.090	0.103	0.092	0.076	0.071	0.070	0.075	0.073	0.054	0.050	0.087
2007	0.078	0.071	0.069	0.076	0.070	0.071	0.073	0.073	0.073	0.069	0.065	0.140
2008	0.072	0.075	0.077	0.198	0.125	0.069	0.068	0.072	0.069	0.065	0.075	0.109
μ	0.086	0.077	0.087	0.115	0.090	0.074	0.075	0.078	0.076	0.067	0.067	0.107
σ	0.014	0.008	0.017	0.056	0.025	0.008	0.009	0.009	0.008	0.011	0.013	0.024

Table 5-8: Monthly ratios to average annual cost for the generated operating cost for the Shuqiq seawater desalination plant using 2nd approach class ranking.

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.109	0.095	0.109	0.097	0.081	0.075	0.074	0.080	0.078	0.057	0.053	0.092
2001	0.089	0.072	0.097	0.093	0.087	0.083	0.086	0.088	0.085	0.079	0.075	0.090
2002	0.091	0.073	0.099	0.095	0.088	0.085	0.088	0.090	0.086	0.080	0.077	0.092
2003	0.070	0.063	0.062	0.068	0.063	0.063	0.066	0.065	0.066	0.062	0.059	0.125
2004	0.077	0.070	0.069	0.076	0.070	0.070	0.073	0.073	0.073	0.068	0.065	0.139
2009	0.078	0.082	0.084	0.215	0.136	0.075	0.074	0.078	0.075	0.070	0.082	0.119
2010	0.110	0.096	0.110	0.098	0.081	0.076	0.075	0.080	0.078	0.058	0.053	0.093
μ	0.089	0.079	0.090	0.106	0.087	0.075	0.077	0.079	0.077	0.068	0.066	0.107
σ	0.016	0.013	0.019	0.049	0.024	0.007	0.008	0.008	0.007	0.010	0.012	0.020

Table 5-9: Monthly ratios to average annual cost for the generated operating cost for the Shuqiq seawater desalination plant using 3rd approach class ranking**.**

Year	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
2000	0.084	0.076	0.075	0.082	0.076	0.076	0.079	0.079	0.079	0.074	0.071	0.151
2001	0.089	0.072	0.097	0.093	0.087	0.083	0.086	0.088	0.085	0.079	0.075	0.090
2002	0.070	0.073	0.075	0.192	0.122	0.067	0.066	0.070	0.067	0.063	0.073	0.106
2003	0.091	0.079	0.091	0.081	0.067	0.063	0.062	0.066	0.065	0.048	0.044	0.077
2004	0.077	0.070	0.069	0.076	0.070	0.070	0.073	0.073	0.073	0.068	0.065	0.139
2009	0.102	0.082	0.111	0.106	0.099	0.095	0.098	0.100	0.097	0.090	0.086	0.103
2010	0.110	0.096	0.110	0.098	0.081	0.076	0.075	0.080	0.078	0.058	0.053	0.093
μ	0.089	0.078	0.090	0.104	0.086	0.076	0.077	0.079	0.078	0.068	0.067	0.108
σ	0.014	0.009	0.017	0.040	0.019	0.011	0.012	0.012	0.011	0.014	0.014	0.027

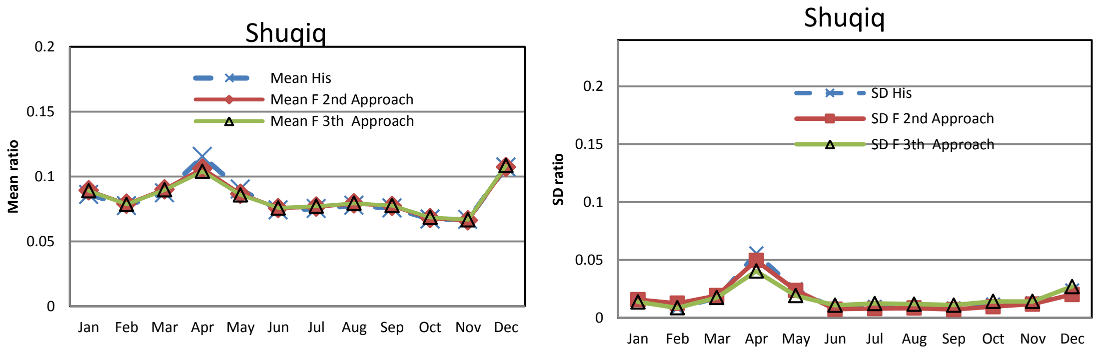

Figure 5-2: Comparison of mean and standard deviation of ratio of each months' value for historical (M. His.) and generated data (2nd and 3rd approach) of the Shuqiq seawater desalination plant.

The final results from the other seawater desalination plants were validated in the same way by comparing the mean and standard deviation ratios for the observed and generated monthly costs, as seen in Figures 5-3 to 5-5. All these comparisons provided a good match in mean ratio, except that there were slight differences in December for Jubail 1, 2 and RO, due to previous accumulated expenses from the year 2008 in December, which was an unusual occurrence (SWCC, 2009). Also there are some differences in standard deviation ratios in the validation results of the generated data for the cases of Yanbu 1, Shuiba 1, Shuiba 2, and Khobar 3, as seen in the comparison figures (Figures 5-3, 5-4, 5-5). These differences are due to the variation in the distribution of the data about the mean between observed monthly costs and generated costs. These differences are due to the variation in the dispersion of the data about the mean between observed monthly costs and generated costs. Despite all the above differences, the results give a good indication for using a method of fragmentation to generate the monthly costs of water production from the annual cost for all the seawater desalination plants used in this study.

In order to select the best approach (among the two) which is suitable for class ranking and generation of the missing monthly costs for this case study, the comparisons were made between second approach (R. Srikanthan & McMahon,

1982) and third approach (Silva & Portela, 2012; Silva, 2010) only. While some of the plants give same results for both approaches, as can be seen from Figure 5-5, others plants give good indications that the 2nd approach is more suitable than the 3rd approach in the current study, as is clear from comparison of the figures of the Shuqiq, Jubail 1, Yanbu 1, Yanbu R, Jeddah 3, and Jeddah RO1 desalination plants. For example, In Yanbu RO, the mean of the months ration for the generated Aprils by the 3rd approach was 0.12637 while in the 2nd approach the match with the historical data at 0.10496 (see Figure 5-3). Another example was Jeddah 3, where the means of the months ration for the generated Marches, Novembers and Decembers obtained by the 2nd approach, at 0.07479, 0.10308, and 0.13961, are closer to the historical figures, at 0.0846, 0.08275, and 0.11571, than those for the 3rd approach, at 0.06966, 0.11342, and 0.16004, respectively (see Figure 5-4). The results of the 2nd approach have hence been used as monthly operating costs in the final data table that will be used in the development of the monthly cost prediction model.

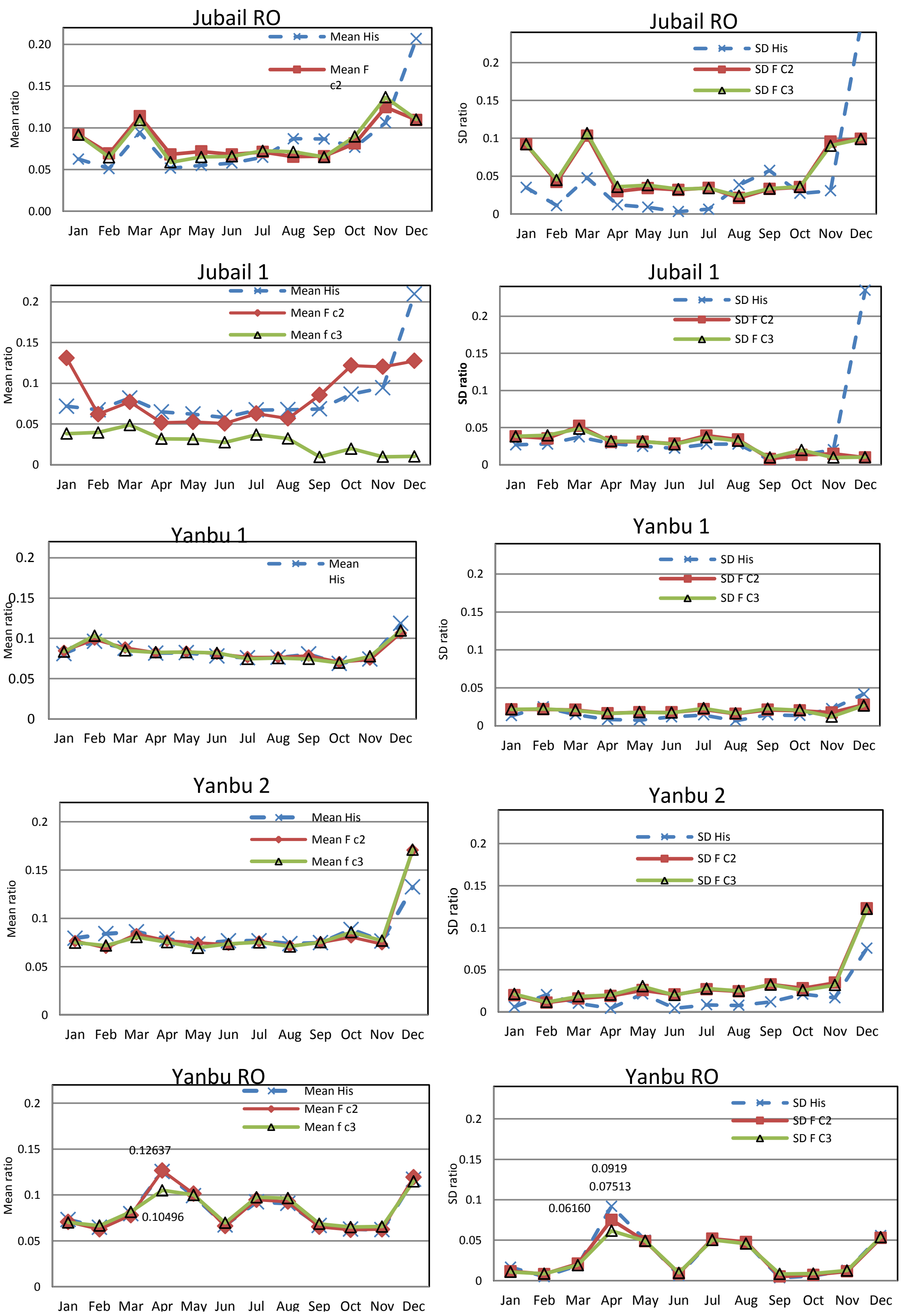

Figure 5-3: Comparison of mean and standard deviation of ratio of each months' value for historical (M. His.) and generated data (2nd and 3rd approach) of the Jubail RO, Jubail 1, Yanbu 1, Yanbu 2, Yanbu RO seawater desalination plants.

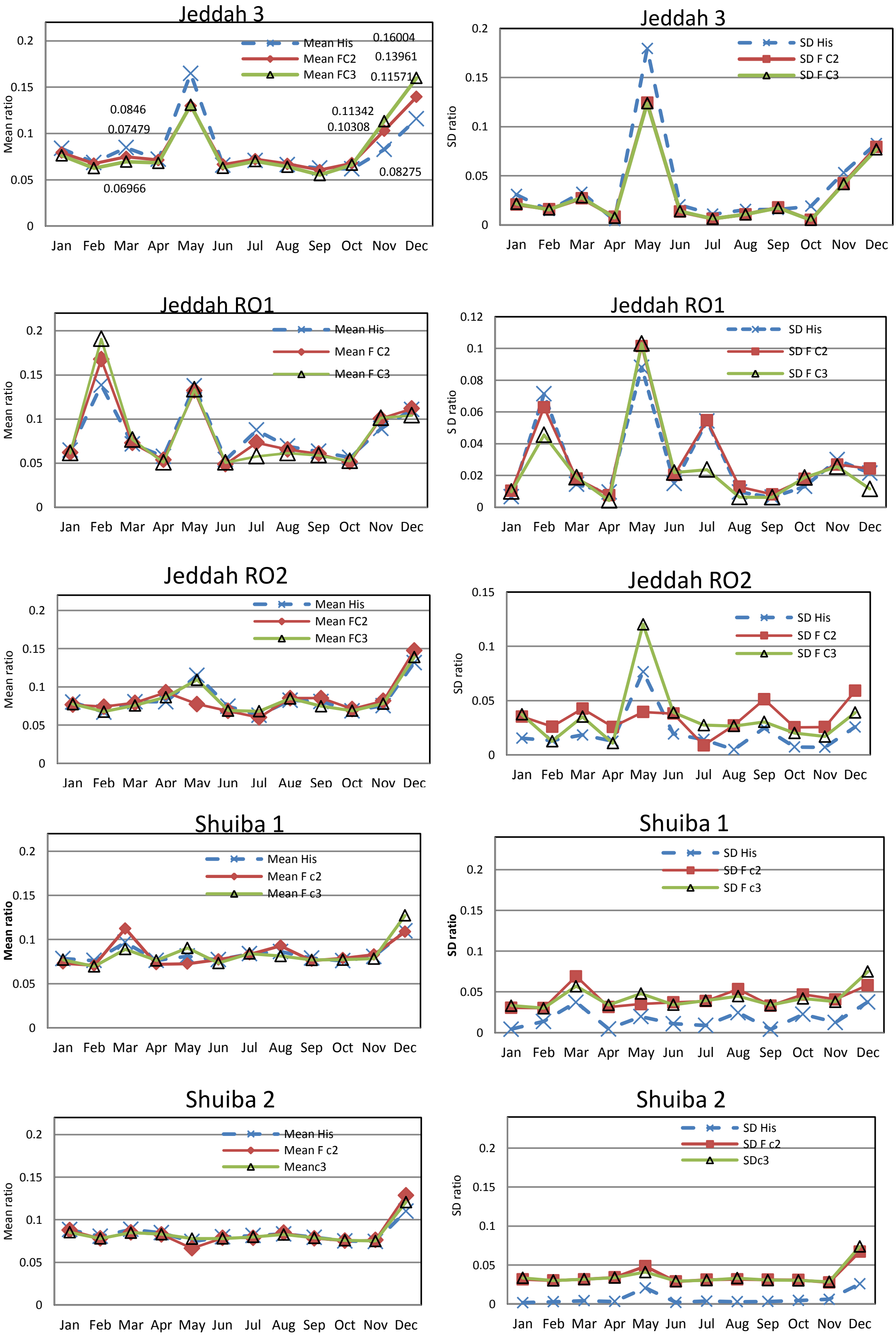

Figure 5-4: Comparison of mean and standard deviation of ratio of each months' value for historical (M. His.) and generated data (2nd and 3rd approach) of the Jeddah 3, Jeddah RO1, Jeddah RO2, Shuiba 1, and Shuiba 2 seawater desalination plants.

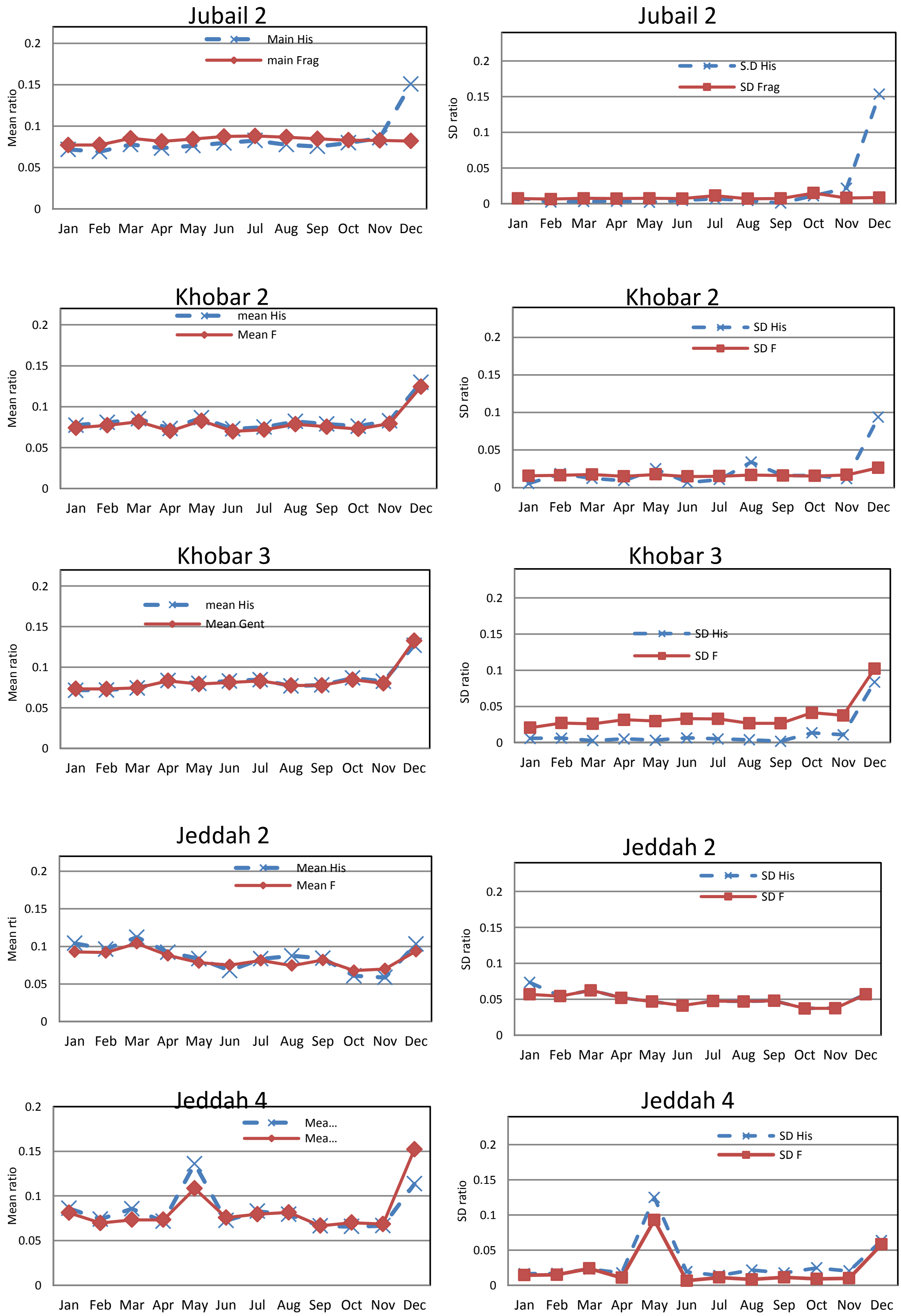

Figure 5-5: Comparison of mean and standard deviation of ratio of the months' value for historical (M. His.) and generated data (2nd and 3rd approach) of the Jubail 2, Kohbar 2, Kohbar 3, Jeddah 2, and Jedah 4 seawater desalination plants.

5.7. Summary

An attempt has been made to understand the relationship between the average annual unit cost of water production and total water production of sea water desalination plants in Saudi Arabia. Generally, companies forecast their budgets based on the monthly cash budget forecasting and so accuracy of estimation is one of the most important issues. The monthly operational data has been collected because the allocation of the monthly operation cost of water production throughout the whole year is almost directly linked to water demand, which is higher throughout the summer season, and the budget estimation is predicted based on the monthly cash budget forecasting.

Because some of the monthly costs were missing, the method of fragments has been used to disaggregate the annual operation cost to monthly costs. According to the literature, three approaches have been evaluated to disaggregate annual value to monthly values by applying method of fragments. All these approaches have the same way to generate the fragments of monthly values of the years that do have historical monthly values. The difference between them is the way of selecting an appropriate fragment from the historical data that can be used to generate monthly values of the years where monthly values are missing.

In the current study, the first approach (Svanidze, 1964) cannot be used because the number of historical years with monthly data available are less than the years with missing monthly data which need to be disaggregated, as mentioned above. The 2nd approach (R. Srikanthan & McMahon, 1982) and 3rd approach(Silva & Portela, 2012; Silva, 2010) can be applied using the available data for defining the classes and selection of the fragments.

In general, the method of fragments is highly suitable for the disaggregation of the annual operating cost of water production from seawater desalination plants to monthly costs. Although both approaches give good results, the second approach, developed by Srikanthan and McMahon (1982), is more accurate for defining the classes and selection of the fragments in this case study.

Chapter 6 - Energy Consumption

6.1. Introduction

Despite the fact that one of the biggest issues of concern in the world today is the rise in energy costs and consumption, and the impact of this on individual countries' economies and the global issue of climate change, many countries, including Saudi Arabia, continue to use high energy desalination treatments to meet their need for water supply. This is largely due to the limited fresh water stocks in these countries combined with the rapidly increasing population.

One of the main parameters found to be affecting the cost and choice of desalting system in previous studies was energy consumption (Al-Karaghouli & Kazmerski, 2013; Al-Sahali & Ettouney, 2007; Dore, 2005; Ettouney & Wilf, 2009; Ghaffour et al., 2013; Karagiannis & Soldatos, 2008; Younos, 2005). It will therefore be important to investigate energy consumption in this study in order to incorporate it in the final cost of desalinated water production. In addition, understanding the factors that influence energy usage at desalination plants is important, as if may inform possible attempts to bring this down.

This chapter discusses about energy consumption for the purpose of water production at seawater desalination plants in Saudi Arabia. The data that underpin the study have been collected over a period of ten years (2001-2010), from the sixteen larger desalination plants in Saudi Arabia. Heat energy consumption in multi-stage flash desalination units has been calculated based on the amount of heat needed by the brine heater and ejector systems. Following this, specific equivalent power work has been calculated in kilowatt hours per cubic metre of water produced (kWh/m^3). Meanwhile, the measure of electrical power consumption has been limited to that of the equipment directly related to the desalination process, such as brine recycling pumps in MSF technology or high pressure pumps in reverse osmosis technology, as well as equipment for auxiliary systems, such as seawater filtration and screening systems. Therefore, this chapter isolates the energy component of the production cost for each plant.

6.2. Energy Calculation-Background Theory

Sea water desalination plants in Saudi Arabia, from which the data for the current study have been collated use mainly two techniques, namely reverse osmosis (RO) and multi stage flash (MSF). So, electrical power consumption needs to be estimated for the RO and MSF desalination plants and thermal energy for the MSF desalination plants. It is worth noting that the steam requirements for the MSF units in Saudi Arabia are provided by the boiler in a co-generation plant. These plants produce electrical power through steam turbines and distilled water through desalination units or what is called a co-generation plant, as shown in the schematic in Figure 6-1 (Al-Mutaz & Al-Namlah, 2004).

In the current study, energy use is compared rather than energy costs, for three reasons. The first reason is that different forms of energy are used in the MSF and RO plants. The second one is that the energy cost was not available. The third reason is because the desalination plants which have been included in current study are co-generation plants, which use the same energy source for two products, water and electricity, as mentioned in sections 2.4.5 and 3.2.1. Because of_the different forms of energy used in MSF and RO plants, there is a need to find a method to evaluate energy consumption based on a common unit, for comparative purposes. Equivalent mechanical work in kwh/m^3 has been used to express applied energy (A1-Sofi & Srouji, 1995; Darwish et al., 2002; McGinnis & Elimelech, 2007). This method is an effective way to estimate and compare the value of process heat in thermal desalination systems and also allows costing of the process steam supplied for the desalination process (McGinnis & Elimelech, 2007).

6.3. Equivalent Work

In this method, thermal energy is assigned as an electrical energy value. This assumes that the steam used to supply energy to the desalination process, which is extracted from a steam turbine (Fig. 6-1), could have been used to generate electricity. The energy conversion from thermal to mechanical and eventually to electrical in a boiler turbine generator is governed by Equation (6-1) (A1-Sofi & Srouji, 1995) . In the desalination process, the number of kg of steam required to generate a kg of water is given by gained output ratio (GOR) , which is the ratio between the weight of distilled water produced, m_d (kilograms) and weight of steam m_s (kilograms) consumed in the desalination process (A1-Sofi & Srouji, 1995), see Equation 6-2. Thus, evaluation of thermal energy can be carried out by calculating the energy of the steam supplied to the desalination unit in terms of electrical generation, using power lost, as in Equation (6-3) (McGinnis & Elimelech, 2007):

$$W_{eq} = m_s * (H_{su} - H_{sc}) * E_{st} \tag{6-1}$$

$$GOR = \frac{m_d}{m_s} \tag{6-2}$$

$$W_{eq} = \frac{1000\ kg_{water\ product}(H_{su} - H_{sc}) * E_{st}}{GOR} \text{ x } 0.000277\ \frac{kWh}{kJ} \tag{6-3}$$

E_{st} is the efficiency of the steam turbine generator, %; H_{su} is the enthalpy of inlet steam to the desalination process (kJ) of heat per kilograms of steam (kJ/kg), and H_{sc} is the enthalpy of the steam at the point where it is extracted from the steam turbine. In Equation 6-3, the figure 0.000277 is the coefficient transformation from kilojoules (kj) to kilowatt hours (kwh) (Green & Perry, 2007) and the result is multiplied by 1000 kg of water to give a specific heat duty in terms of m^3 water.

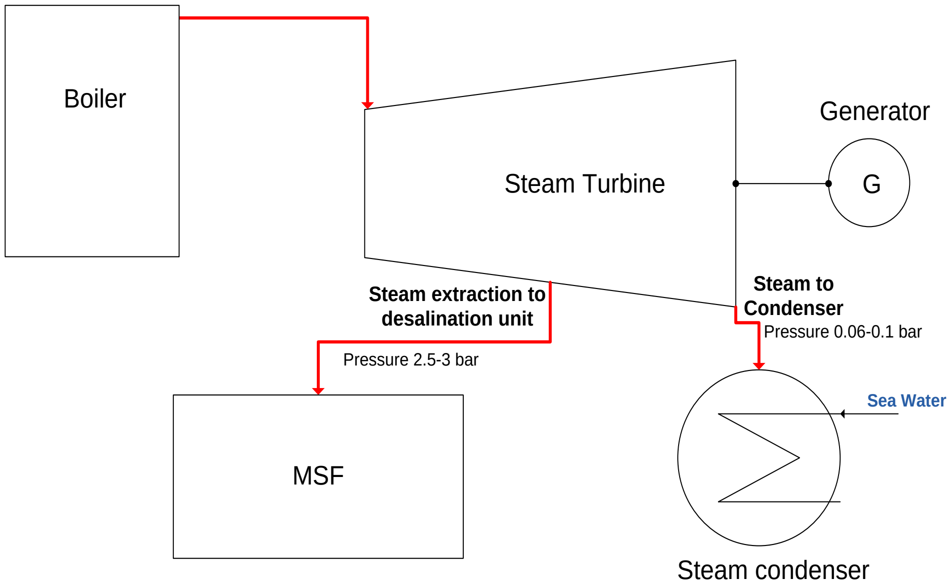

Figure 6-1: Steam turbine supplying a MSF desalination unit.

6.4. Energy Consumption

For the seawater desalination plants being used in the current study (Table 3-1) the energy consumption to produce one cubic meter of desalinated water is estimated. As mentioned above, these plants use two types of desalination techniques. In case of RO desalination plants, the energy consumption (kWh/ m^3) has been estimated as a ratio of total electrical energy (kWh) consumed and total water production (m^3), for the same time period in each RO plant.

For MSF, both the thermal energy as well as the electrical energy directly consumed must be accounted for. The electrical energy equivalent of the thermal energy for MSF plants was estimated by calculating the specific equivalent work (kWh) using Equation (6-1). For each MSF desalination plant, there is a unique thermal specification for its desalination units, as shown in Table 6-1. To account for the power losses at all the desalination plants in this study E_{st} is assumed to be 90% based on the actual value of steam generator turbine efficiency of Jubal 2, Khobar 2, and Kohbar 3, Jeddah 4, shoiba 2 and Shuqiq where efficiencies were 90%, 88%, 90%, 90%, 95%, and 90% respectively. H_{sc} is taken as 2335.5

kJ/kg, based on the average seawater temperature in Saudi Arabia, which is around 28°C (SWCC, 2011) and using tabular data that relates condenser temperature and seawater cooling temperature, as developed by Ganan et al, where they estimated the enthalpies at the inlet of the turbine condenser $\mathrm{H_{sc}}$ (Fig. 6-1) at different cooling water (sea water) temperatures (Gañán at al., 2005).

Directly consumed electrical energy in MSF desalination plants was estimated based on energy consumption for one hour operation (kWh) of each plant. This power requirement data has been derived from the production information system (PIS) in SWCC and the operation and maintenance manuals of the plants, as mentioned in section 3.2.1. The electric power requirement for one hour of operation of the MSF desalination plants surveyed are summarised in Table 6-2. All these values were based on the current state of the plants and include the energy consumed by the main equipment and plant auxiliaries, such as sea water intake pumps and filtration systems, and chlorination systems. Thus, the total energy consumption for one m³ of distilled water in any thermal desalination plant (MSF, MED) is calculated by applying the following equation in the same time period (t).

$$\mathrm{E_{total}} = \frac{\mathrm{W_{eq(t)}} + (\mathrm{Elec_{One\ hour}} * \mathrm{Hours_t})}{\mathrm{P_t}} \qquad (6\text{-}3)$$

where $\mathrm{E_{total}}$ is energy consumption in kWh/ m³ at time period t, which is one month in this study; $\mathrm{W_{eq(t)}}$ is the equivalent work of thermal energy converted to electrical energy in kWh (Equation 6-1); $\mathrm{Elec_{One\ hour}}$ is the total electric power consumption for one hour of operation in kW (Table 6-3); $\mathrm{Hours_t}$ represents the total operating hours of the MSF desalination unit in service during time period t; and $\mathrm{P_t}$ is the total water production in m³ during time period t.

To get a good indication of the extent of energy consumption in the seawater desalination plants in Saudi Arabia, and to relate this with other important technical and economic parameters, the average energy consumption has been evaluated with reference to five factors: type of desalination techniques; average monthly water production; average total dissolved solid (TDS) in the inlet sea water; average TDS in the distillate water; and the distillate water unit cost for each plant. The results are shown in the next chapter.

Table 6-1: Thermal specifications of the MSF desalination units

Plant	No. of units	Unit installed capacity m³/ Day	Steam to brine heater and before			Steam to ejectors			
			Temperature °C	Pressure bar	Enthalpy(H_{su}) Kj/Kg*	Temperature °C	Pressure bar	Enthalpy Kj/Kg*	Ton/ Operation Hour
Jubail 1	6	22,955	112	1.2	2698.1	210	18	2803.28	1.4
Jubail 2	40	23,697	120	1.4	2712.3	220	17	2837.5	2.9
Khobar 2	10	22,300	135	1.8	2729.8	230	18	2859.1	3.5
Khobar 3	8	35,000	127	1.5	2715.8	230	18	2859.1	5
Jeddah 2	4	11,022	160	3.7	2776.5	200	11.5	2817.6	1.6
Jeddah 3	4	22,089	130	1.6	2720.9	220	16	2843.1	1.5
Jeddah 4	10	22,158	135	1.81	2729.7	220	16	2843.1	2
Yanbu 1	5	21,615	130	2.0	2726.9	190.7	12	2790.1	2.86
Yanbu 2	4	36,000	134	2.26	2732.8	285	14.82	3005.7	3.85
Shuiba 1	10	22,300	130	2.5	2721.9	220	12	2864.5	2.87
Shuiba 2	10	45,455	131.2	2.8	2721.5	230	18	2859.1	3.6
Shuqeq	4	24,254	121	2.05	2707.4	195	9.5	2817.6	2.4

* Kj/Kg: Enthalpy measurement (Kilo-Joules of heat per kilogrammes of steam)

Table 6-2: The hourly electric power requirement for one unit operation at the MSF desalination plants

Plant	Electric power consumption, Kilowatt/ Hour Operation ($Elec_{One\ hour}$)								
	Sea water pumps	Brine recycle pumps	Blowdown pumps	Distillate pumps	Condensate pumps	Ball Cleaning pump	Auxiliary, ejector condenser pumps	Sea water intake electrical equipment	Total
Jubail 1	1633.3	3300.0	160.0	180.0	37.0	5.5	0.0	106.1	5421.93
Jubail 2	811.0	1897.2	106.1	139.5	48.6	3.3	56.0	109.5	3171.15
Khobar 2	1150.0	2040.0	230.0	130.0	102.0	15.0	0.0	161.5	3828.46
Khobar 3	2400.0	3400.0	280.0	230.0	132.0	4.0	0.0	255.7	6701.72
Jeddah 2	778.9	1147.7	77.0	78.6	34.4	2.3	0.0	48.6	2167.51
Jeddah 3	1200.0	2680.0	167.0	61.0	96.0	4.6	0.0	92.5	4301.12
Jeddah 4	1928.0	1926.0	142.0	255.0	42.0	4.6	0.0	102.7	4400.28
Yanbu 1	680.0	2100.0	150.0	155.0	37.0	4.0	100.0	75.8	3301.78
Yanbu 2	2040.0	5400.0	160.0	335.0	132.0	10.0	0.0	169.8	8246.84
Shuiba 1	1330.0	3700.0	110.0	195.0	90.0	2.4	0.0	123.6	5550.92
Shuiba 2	2440.0	6100.0	170.0	540.0	160.0	4.0	0.0	206.1	9620.08
Shuqeq	1230.0	4700.0	90.0	140.0	53.0	7.0	0.0	150.9	6370.91

6.5. Results and Discussion

Energy consumption is one of the most important parameters by which to evaluate the efficiency of the desalination process. This chapter has estimated and compared the energy consumption for water produced from the sixteen larger sea water desalination plants in Saudi Arabia; all the plants use one of two types of energy, electrical power and thermal energy (Equivalent work). Regardless of the type of fuel or boiler efficiency, the evaluation of heat consumption has been based on the actual process in which steam is supplied to the desalination system. Full results of the energy consumption in each month (2001-2010) are presented in Appendix C; only the summary is discussed in the following sections.

As shown in Fig 6-2 there are quite significant differences in the energy consumption for MSF desalination techniques, compared with the RO technique. It can be seen that one metric cube of fresh water production consumes between 14.3-23.4 kilowatt hours (kWh), if MSF desalination is used, while it will consume 7.1-10.4 kWh if RO is applied; this finding is in agreement with previous studies (Al-Sahali & Ettouney, 2007; Ettouney & Wilf, 2009), as mentioned in section 2.4.5. The difference is in the highest maximum consumption in plants in the current research, where the consumption values were 23.4 kWh and 10.4 kWh in the Kohbar 2 MSF and Jubail RO plants, respectively, while it was 18 kWh and 8 kWh in the MSF and RO plants as per the previous studies (Al-Sahali & Ettouney, 2007; Ettouney & Wilf, 2009). This variance may be due to the low efficiency of Khobar2 and Jubail RO in the time period of the current research (SWCC, 2011). The electrical power consumption accounted for 28.3% of the total energy consumption in the MSF desalination plants.

The energy consumption varies from plant to plant, even when they are at the same location and use the same desalination technique, because of different technical specifications, capacity, different operating conditions of plants and the time of commission. For example, the consumption in AlKhobar 2 was higher (23.37 kWh/ m^3) compared to Alkhobar 3 (20.12 kWh/ m^3), despite the fact that it is in the same location and uses same desalination techniques. One of the reasons is the unit and plant capacity in Alkhobar 3 which are 35000 m^3/day and 280000 m^3/day respectively while at AlKhobar 2 the unit and plant capacity are 22300 m^3/day and 223000 m^3/day respectively (see Tables 6-1 and Table 6-2). Also, the failure in tubes of the heat exchanger used in stage one in most of the MSF desalination units in Alkhobar 2, due to the age of the plant (commissioned 1983) was causing higher energy consumption. Some parts of the plant reduced their energy consumption during the period of this study, due to life extension projects at the sea water desalination plants in Saudi Arabia (SWCC, 2011). For instance, the plant Jeddah 4 showed improved energy consumption: from 20.84 kWh/ m^3 between 2000 and 2006, down to 17.55 kWh/ m^3 between 2006 and 2010. In plant Jeddah 2, the energy consumption was quite high, at 20.26 kWh/ m^3 with poor productivity at 27.68 thousand m^3 per day while installed capacity was more than 44 thousand m^3 per day. For this reason operations at the plant were stopped in 2008.

In contrast, the energy consumption at RO desalination plants varied from 7.1 kWh/ m^3 in the Yanbu RO plant to 10.4 kWh/ m^3 in the Jubail RO plant. The consumption was found to be relatively higher in the Jubail RO plant at 10.4 kWh/ m^3 compared to values quoted in previous studies of 2 to 3.5 kWh/ m^3 for new plants and 6 to 8 kWh/ m^3 for old plants (Lomax, 2009; Sommariva, 2010). Due to this, the energy consumption at the RO desalination plants included in the current study (Jubail RO, Jeddah RO1 and RO2, and Yanbu RO plants) needs to be re-investigated, taking into account the details for energy consumption and other important parameters, such as the application of energy recovery devices (ERD) and the types of RO membranes used.

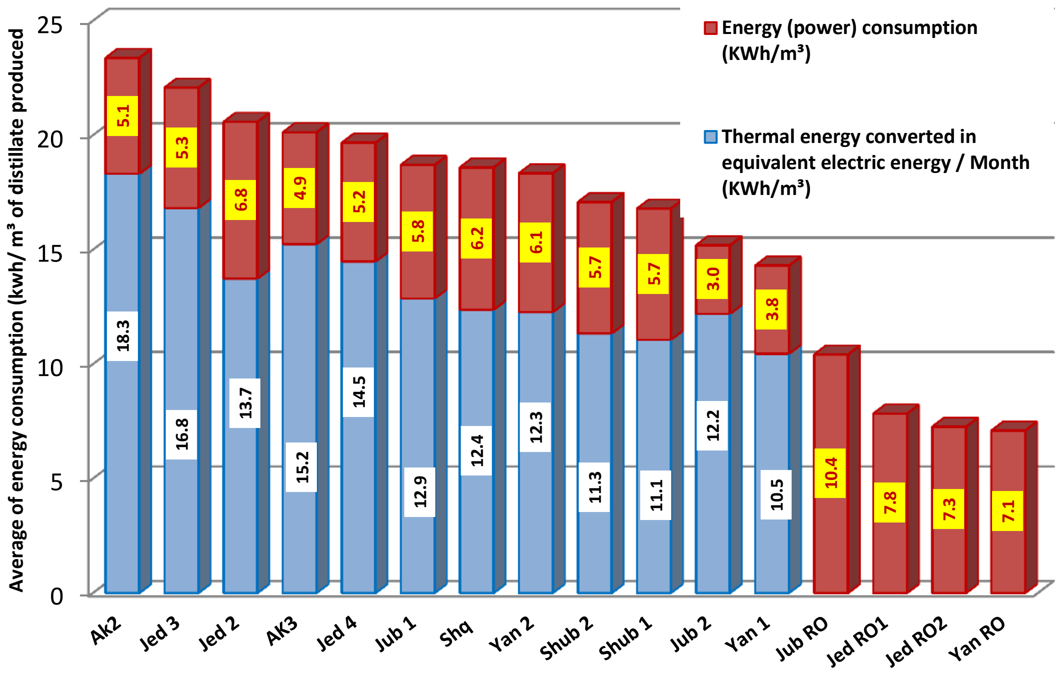

Figure 6-2: Average thermal and electricity energy consumption (kWh/ m³) of water produced from sea water desalination plants in Saudi Arabia.

6.6. Summary

The energy consumption for water production at the sixteen larger sea water desalination plants in Saudi Arabia has been evaluated. Two types of energy were found to be used at these plants: electrical power and thermal energy. Converting thermal energy to equivalent work is an effective way of estimating and comparing the value of thermal energy consumed in sea water desalination systems and the costs of the steam being supplied to a desalination system.

There was a significant difference in the energy consumption between RO and MSF desalination plants, it was found that the MSF technique consumed more than double the energy of the RO technique. Therefore, to improve output water quality, there will be more energy consumed. The electrical power consumption accounted for a considerable part (28.3%) of the total energy consumption at MSF desalination plants, leading us to consider this type of consumption for any energy study of the thermal desalination process.

Chapter 7 - Results and Discussions

7.1. Introduction

The aim of this chapter is to present the results of the development and testing of the predictive models. Along with monthly total unit cost and total water production, other technical factors have been collected which comprise average sea water salinity, average product water salinity, and average energy consumption of one metric cube of distilled water. The selection of these factors was based on their importance in water cost, as mentioned in Chapter 2, as well as the availability of historical data. Incidentally, the aim of this research is to understand factors identified in previous studies that significantly affect the cost of production at desalination plants, as mentioned in section 2.9.5 and use these to develop a predictive model for production cost of water produced from seawater desalination plants in Saudi Arabia.

In the next section, the outcome of the pre-processing of the data to assure its quality is presented. The processing also involved the correlation analysis to identify the most significant predictor variables that will be used in the prediction model. This is then followed by the model calibration, verification and validation.

7.2. Pre-processing

As explained in Chapter 3, the processing of the monthly data was carried out to identify and replace outliers, as well as get an indication as to the probability distribution of the cost data. The pre-processing also involved cross-correlation analysis to identify significant predictor variables for the monthly cost model.

7.2.1. Outliers and Indicative probability distribution

As discussed in Chapter 3, outliers were identified using the method of z-score (Equation 3-1). The monthly data collected for 2001 to 2010, including those filled by disaggregation gave 1783 for the model development. This is less than the theoretical possible of 1920 because of Jeddah 2 was discontinued at the end of 2007 and so had no data for 2008-2010.

The mean and standard deviation of the production cost of monthly total unit cost (TUC) (Appendix A) were 4.15 SR/$m^3$and 3.00 SR/m^3 respectively. When applied in equation (3-1), it was found that there are ten points that can be considered as outliers, see Table 7-1. Six of these points belong to the Jubail RO desalination plant. The other four points belong to the data collected from Jeddah 2 and Shuiba 1, each of them with two points. The highest probability of occurrence of these outlier costs was 0.488% in November 2007 in the Jubail RO plant, which is unlikely to occur. Because of this result, these readings have been excluded, leaving 1773 measurements for the models development.

The histograms of the monthly data with and without the outliers are compared in Figure 7-1. As Figure 7-1 shows, the removal of the outlier has produced a less skewed data set.

Table 7-1: Monthly total unit costs considered as outliers.

	YEAR	MONTH (M)	Plant	Monthly Total Unit Cost (SR)/m³	Z-score(TUC)	Probability of occurring (%)
1	2005	January	Jubail RO	13.638	3.158807	0.0816
2	2006	December	Jubail RO	16.49667	4.110737	0.002
3	2007	January	Jubail RO	37.01297	10.94262	0
4	2007	November	Jubail RO	11.91175	2.58397	0.488
5	2009	January	Jubail RO	14.27801	3.371928	0.0376
6	2009	February	Jubail RO	87.19517	27.65317	0
7	2003	December	Jeddah 2	14.80411	3.547118	0.02
8	2004	January	Jeddah 2	14.85666	3.564616	0.0185
9	2009	October	Alshuaibh 1	32.33085	9.383482	0
10	2010	December	Alshuaibh 1	37.3634	11.05931	0

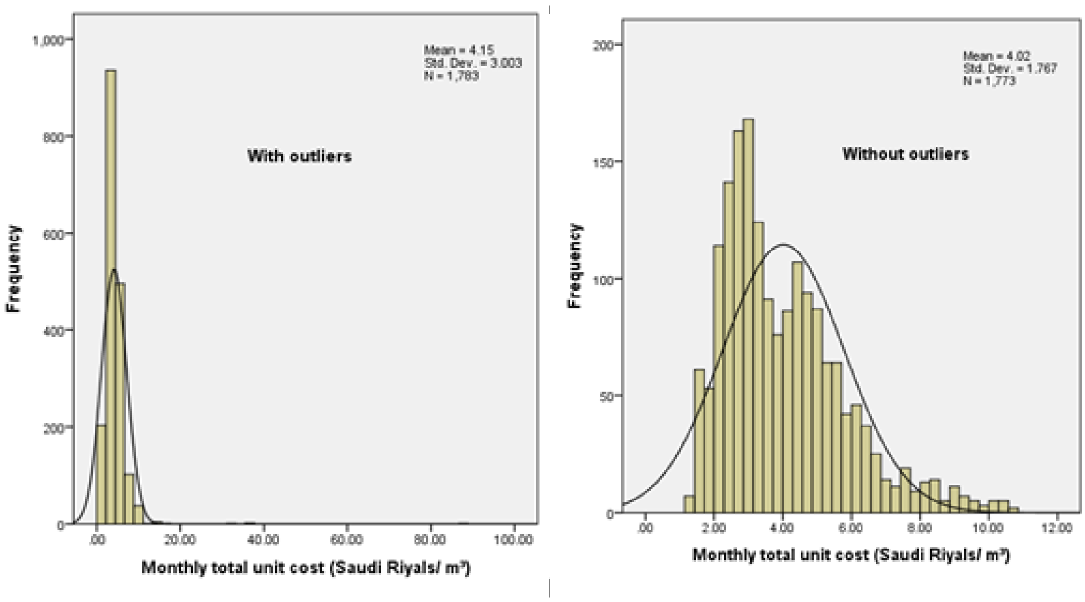

Figure 7-1: Frequency distribution diagram for the monthly total unit cost (a) left: raw data (b) right: with outliers removed

7.2.2. Correlation Analysis

The final data used for cost models development (Appendix D) will be used after eliminating the outliers, as mention in the previous section. The SPSS static software program has been used. From the analysis icon in SPSS, correlate was selected, then the variables were selected In which case to carry out a two-tailed (a significance level of 0.05) and obtain the Pearson correlation coefficient as mentioned in section 3.3.2. The results of the correlations between the identified variables are given in Table 7-2. As shown in Table 7-2, the correlation is significant in most of the variables; the only non-significant results are between sea water salinity (SW TDS) and monthly total water production (TWP), and between sea water salinity and monthly total unit cost (TUC) where the significances were 0.126 and 0.09 respectively.

The correlation between the total unit cost (TUC) and other variables are low. The best correlation with TUC is total water production (TWP), at negative correlation coefficient of (-0.304). The second best correlation with TUC is the unit energy consumption (EC), at positive correlation coefficient of 0.275. Although the energy consumption is responsible for about 50% of the total desalted water cost, as found in a previous study (Al-Karaghouli & Kazmerski, 2013), the low correlation between TUC and EC in current study relates to the low price of fuel, that is highly subsidized by the government (Ghaffour et al., 2013) as discussed in section 2.4.5.

The relationship between TUC and sea water salinity (SETDS) was very weak, at correlation coefficient of 0.044 which does not match findings of previous studies, as discussed in section 2.4.5. While most previous studies have found a relationship between total unit cost and desalination techniques, the current study has found a low correlation between unit cost and desalination techniques. However, current result matches that of Borsani and Rebagliati's study, which concluded that the cost of desalted water for large RO, MSF and MED desalination plants was almost the same (Borsani & Rebagliati, 2005). In general, the best correlations between variables were between the types of desalination techniques and energy consumption and the correlation between types of desalination techniques and product water salinity, while the best correlation with total unit cost was total water production, as mentioned above. On the other hand, there was no correlation between sea water salinity and monthly total water production, and between sea water salinity and monthly total unit cost (TUC), which match with the significant results, as mentioned above.

Table 7-2: Correlation coefficient between the variables

		Energy (EC)	Sea water (SW TDS)	Product water (PW TDS)	Desalination Technique (DT)	Monthly water production (TWP)	Monthly unit cost (TUC)
Energy (EC)	Correlation	1	.071	-.394	-.751	.090	.275
	Significance		.005	.000	.000	.000	.000
Sea water (SW TDS)	Correlation	.071	1	-.138	-.089	.037	.041
	Significance	.005		.000	.000	**.126**	**.090**
Product water (PW TDS)	Correlation	-.394	-.138	1	.710	-.325	.157
	Significance	.000	.000		.000	.000	.000
Desalination Technique (DT)	Correlation	-.751	-.089	.710	1	-.310	-.136
	Significance	.000	.000	.000		.000	.000
Monthly water production (TWP)	Correlation	.090	.037	-.325	-.310	1	-.303
	Significance	.000	**.126**	.000	.000		.000
Monthly unit cost (TUC)	Correlation	.275	.041	.157	-.136	-.303	1
	Significance	.000	**.090**	.000	.000	.000	

7.3. Calibration and Validation of Regression Models

As noted in the previous section, the highest correlation with the unit production costs are those of the energy consumption and total water production. Consequently, both of them qualify to be used as independent variables in the cost prediction model. However, for this to happen, both the energy consumption and total water production must not be significantly correlated, which is not the case in the result in Table 7-2. Thus, only one of the two variables can be used in the prediction and the decision was therefore taken to use the variable that is commonly available. As noted previously, energy consumption data is not available for all the plants in Saudi Arabia; indeed, data on energy were only available for RO plants while the consumption for the other desalination technologies had to be derived from first principles (see Chapter 6). Consequently, total water production was selected as the lone independent variable.

In conclusion, it can be said that there is a reasonable relationship between total water production and total unit cost. In contrast, there is a relatively lower correlation between water production unit cost and product water TDS, and desalination techniques. The energy consumption cannot be used as an independent variable with total water production in same multi-regression model, as mentioned above. Moreover, there was no relationship between seawater TDS and total unit cost. Consequently, the study employed total water production as the lone predictor variable for the model of the cost of water produced from seawater desalination plants in Saudi Arabia.

Figure 7-2 is a plot of the monthly unit cost against the total water production, which clearly shows an inverse relationship between the cost and the total water production. Based on these, several regression models were considered as follows:

Linear $$Y = a + (b_1 \; X) \tag{7-1}$$

Logarithmic $$Y= a + b_1 \,(\ln X) \tag{7-2}$$

Power $$Y= a \; X^{b_1} \tag{7-3}$$

Inverse $Y = a + (b_1 / X)$ (7-4)

Exponential $Y = a\, e^{b1\, X}$ (7-5)

where Y is the production unit cost (Saudi Riyals SR), X is the water production (m^3/day), and a, and b_1 are regression coefficients to be estimated by calibration (Harrell, 2001; Field, 2009). The calibration was carried out using the SPSS software tool. For the calibration, 1600 of the data points were randomly selected and used. The remaining 173 were used for the validation. The 1600 data points were calibrated by selecting the regression option from the SPSS analysis, then selecting the curve estimation option. After that, two variable (TUC as dependent and TWP as independent) were selected the and the suggested model equations, which were the Linear, Logarithmic, Power, Inverse, and Exponential equation models.

The model summary and parameter estimates are shown in Table 7-3 from which it is clear that the probability of statistical significance in all models is less than 0.05, which means that the null hypothesis that the regression parameters are zero can be rejected. The performance of the model in fitting the data is also shown in Figure 7-2, from which it is clear that of all the models postulated, three models i.e. the inverse, logarithmic and power models appear to fit the data better than the rest. The evidence provided by the plots in Figure 7-2 is also supported by the coefficient of determination (R^2) which is the proportion of variance in one variable explained by a second variable: the highest R^2 is the best explanation (Field, 2013). In current research, the highest R^2 at 0.281, 0.203, and 0.185 for inverse, logarithmic, and power equations, respectively. Furthermore, the obtained (F-ratio), which is the ratio of how good the model against how bad it is (Field, 2013) for these three models is the highest at 691.6, 450.05, and 401.736 for inverse, logarithmic, and power equations, respectively. To evaluate the accuracy of these models, predicted costs during calibration are compared with historical cost in the X-Y scatter plot (Figure 7-3), which again support the superiority of the three non-linear models.

Table 7-3: Model Summary and Parameter Estimates where total unit cost is the dependent variable and monthly production is the independent variable.

Equation	Model parameters				
	R Square	F	Sig.	Constant	b1
Linear	.093	182.182	.000	4.488	-8.337E-8
Logarithmi	.203	450.055	.000	18.942	-.984
Inverse	.281	691.669	.000	2.763	3643116.359
Power	.185	401.736	.000	113.175	-.226
Exponentia	.094	184.717	.000	4.112	-2.018E-8

Using the model parameter estimates reported in Table 7-3, particular forms of the three non-linear models become:

Logarithmic $$TUC = 18.94 - 0.984\,(\ln P) \quad (7\text{-}6)$$

Inverse $$TUC = 2.76 + (3643116.36 / P) \quad (7\text{-}7)$$

Power $$TUC = 113.175 * P^{-0.226} \quad (7\text{-}8)$$

where TUC is the total unit cost (Saudi Riyals per metre cube) and P is the total water production (metre cube per month).

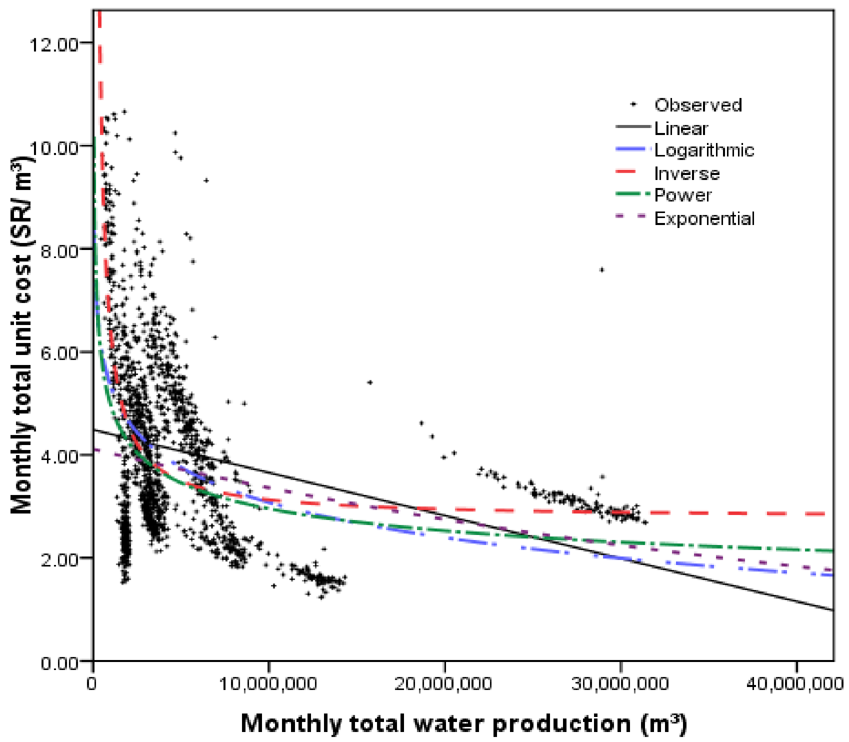

Figure 7-2: The regression models during calibration of the historic data.

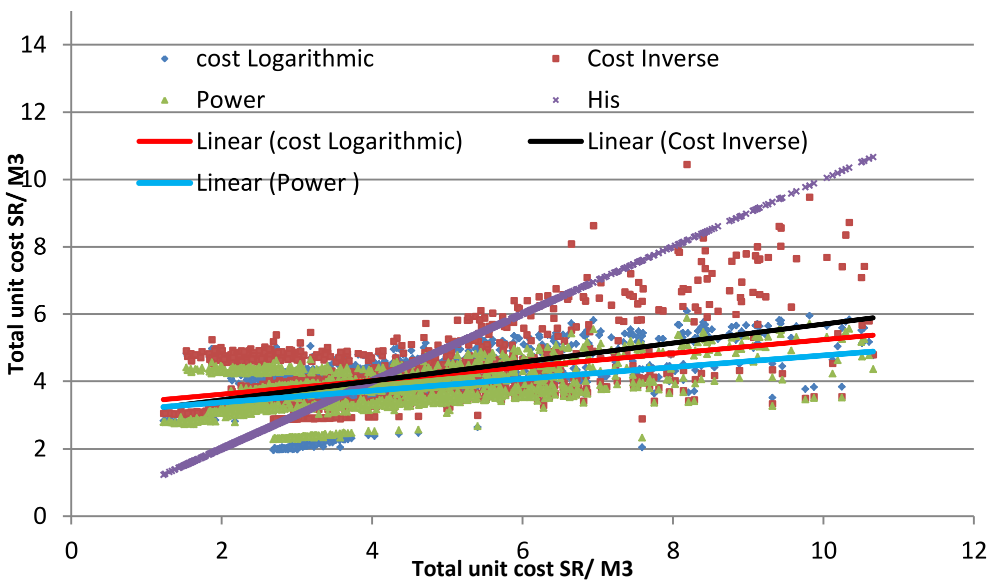

Figure 7-3: X-Y scatter plot of historic cost and predicted cost of the historic data.

The three models were validated using the remaining 173 data sets and the result of the validation is summarized in the X-Y scatter plots in Figure 7-4. When Figure 7-4 is compared with the X-Y scatter plot of the data use for calibration (Figure 7-3), it is easy to note that the performance of the models during validation is as good as during calibration.

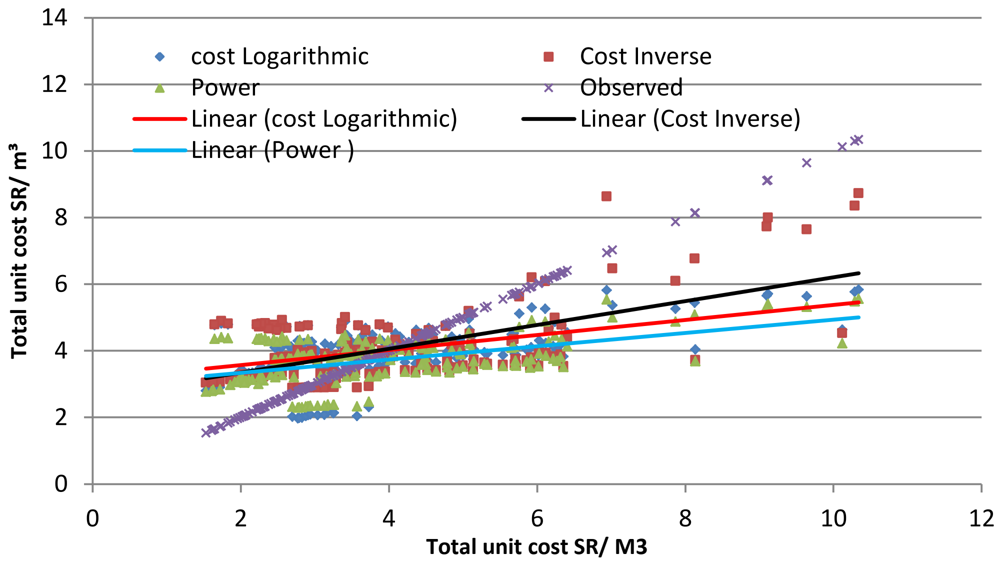

Figure 7-4: X-Y scatter plot of observed and predicted cost during validation.

7.4. Uncertainty assessment of predictive models

A huge uncertainty exists in the available data on total water production (TWP) and total unit cost (TUC), which may translate to similar uncertainties in the model's predictions, as mentioned in Chapter 7. Additionally, because of the shortness of the data available – 10 years, it is certain that the calibrated parameters and hence any prediction of the model will exhibit variability. It is therefore important that this variability is quantified and used to construct the confidence intervals of the prediction for better decision making. This was achieved in the study using Monte Carlo simulation.

Monte Carlo simulation approach involves resampling with suitable probability distribution function and stochastic dependence model to generate equally likely replicates of the historical data. Each of the replicates was then used to estimate the parameters of the predictive models. The resulting population of model parameters were then analysed to determine the mean, standard deviation, and 95% confidence limits. These models offer more useful insights into cost of seawater desalination plants than the use of the purely deterministic options available in the literature, as discussed in section 2.4.6.

7.4.1. Pre-Processing to normalise data

For simplicity, a normal distribution is being adopted for both the TWP and TUC. However, as the sample histograms in Figures 7-5 and 7-6 show, the monthly variables are highly skewed; consequently, possible transformation to remove the skewness is required.

The Box-Cox transformation method presented in section 3.5.1 was used to reduce skewness and normalize the data. The transformation parameter "λ" , that is used in transformation Equation. 3-14, has been estimated by Matlab software, using the Box-Cox transformation. The Box-Cox transformation is one of the functions of the transform time series in financial toolbox of matlab software. Table 7-4 and Table 7-5 show the transformation parameter for TWP and TUC for each month in each desalination plant. By applying the Box-Cox transformation method, there were good improvements in data normality. For example, Figure 7-5 compares the frequency distribution for the TWP in March for the Shuiba 2 plant (plant 35), before and after application of the Box-Cox transformation. In this example, the original data had negative skewness (Hippel, 2010), after the Box-Cox transformation, the distribution became normal. Similarly, the distribution of the TUC in December for the Jubail 1 (plant 23), in Figure 7-6; its positive skew became normal after the Box-Cox transformation. From both examples, it is clear that applying the Box-Cox method produces near-normally distributed data. Other examples of the frequency distribution comparison before and after applying the Box-Cox method have been included in Appendix E.

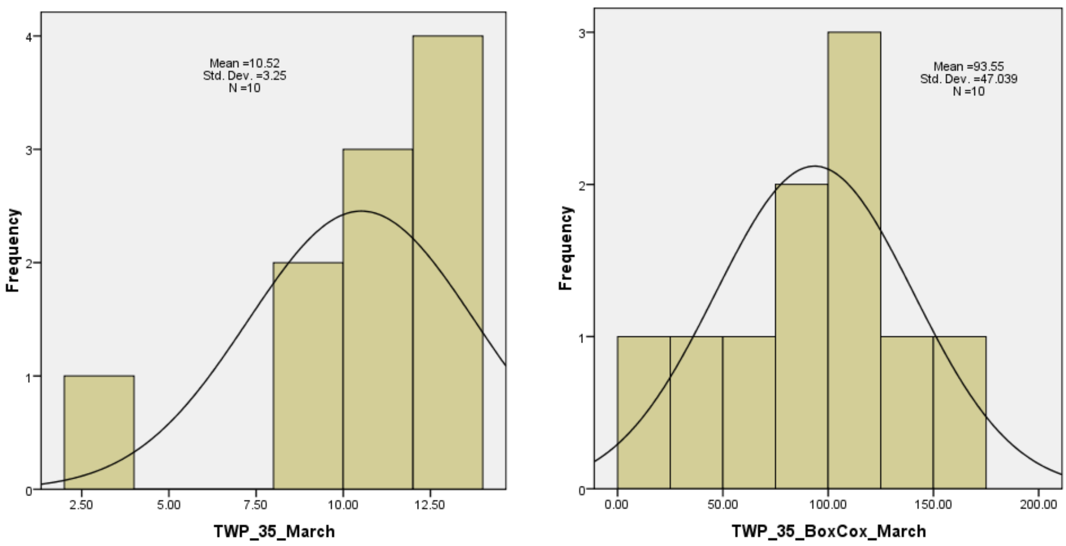

Figure 7-5: Frequency distribution diagram for the total water production (TWP) (a) left: raw data (b) right: transferred data for March of ten years of Shuiba 2 plant.

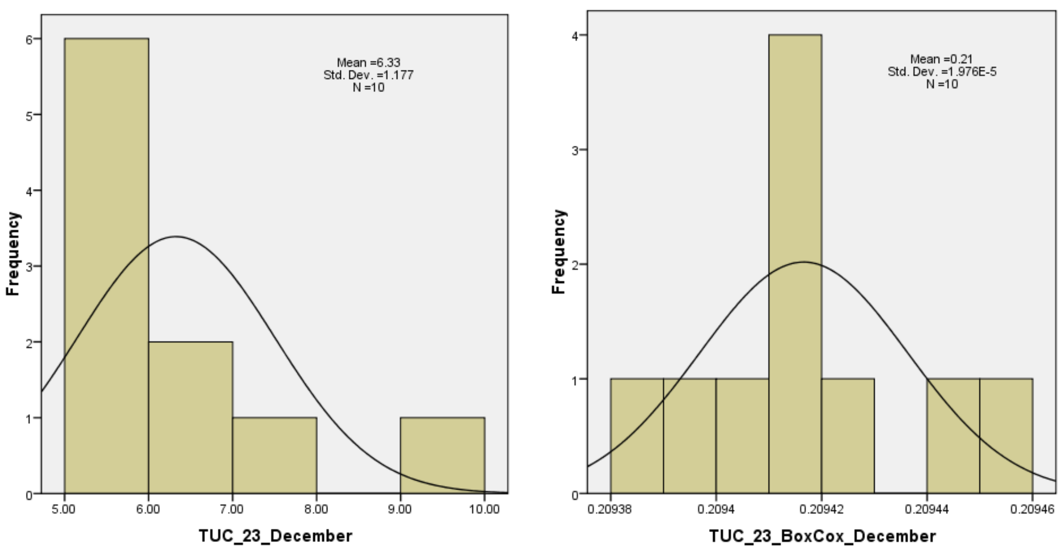

Figure 7-6: Frequency distribution diagram for the total unit cost (TUC) (a) left: raw data (b) right: transferred data for December of ten years of Jubail 1 plant.

Table 7-4: Box-Cox Transformation λ parameters for total water production" TWP".

Plant	AK2	AK3	Jub1	Jub2	JubRO	Yan1	Yan2	YanRO	Jed2	Jed3	Jed4	JedRO1	JedRO2	Shub1	Shub2	Shq
Jan	2.890813	3.237563	2.562125	3.691063	0.79675	5.318875	1.596	3.437063	0.765938	4.215375	-0.567875	0.041875	5.124625	-6.772375	1.718688	3.249063
Feb	2.105375	3.157125	4.630063	2.408875	0.700375	2.712625	2.498	4.243188	1.7125	2.4245	0.135438	0.828	-6.193938	2.152938	1.707563	1.099875
Mar	1.664688	1.567813	2.661625	-2.389563	0.88325	-5.56975	2.622438	0.748313	1.22525	2.689875	1.99625	-3.079875	7.409813	4.188	2.225313	7.159875
Apr	2.204563	4.422375	-1.420688	-5.616	1.04175	0.205625	2.851438	0.741063	1.776375	4.872688	0.65425	5.747313	10.404	2.84425	2.3055	6.717563
May	1.64275	5.02575	1.96675	5.094563	0.928313	2.967938	1.70775	-4.61125	0.956438	3.074125	-1.79325	6.666875	6.234125	2.99725	2.37575	4.755813
Jun	1.999063	7.749688	1.590063	11.39813	1.558313	-0.287125	1.505563	6.138438	1.014188	-2.236688	-0.699813	0.63925	7.97325	2.673813	2.496313	3.535063
Jul	0.66125	11.30913	-0.858313	13.80881	1.116188	-3.021625	4.262063	7.911375	1.98125	8.990938	0.439	10.03631	3.498188	4.438	2.927625	4.199375
Aug	0.115375	12.91588	-1.01975	11.20738	2.178	-3.29525	5.679063	1.457625	1.876313	2.45475	2.269375	5.632125	6.556938	3.589563	2.261	3.853063
Sep	4.19725	7.111688	2.145313	10.24869	0.691188	3.263938	3.363875	2.745875	1.782125	4.081063	2.610875	1.696375	8.905188	2.030375	2.703438	4.351375
Oct	-1.253563	5.078	3.951	8.48	1.545125	6.29125	6.421813	4.485813	1.498125	7.111813	0.494688	7.18575	7.5215	2.326438	3.581938	3.894625
Nov	-1.236063	-0.784875	1.862875	7.786063	1.030875	3.707313	4.78075	5.605875	2.209125	7.326938	-0.167125	4.605563	8.976938	2.992438	2.960688	11.85369
Dec	-4.105813	5.125063	6.073313	6.986813	0.304813	2.779875	3.041625	5.13925	1.438188	6.975125	-0.431188	-4.71925	6.463125	2.237813	3.574875	3.423188

Table 7-5: Box-Cox Transformation λ parameters for total unit cost" TUC".

Plant	AK2	AK3	Jub1	Jub2	JubRO	Yan1	Yan2	YanRO	Jed2	Jed3	Jed4	JedRO1	JedRO2	Shub1	Shub2	Shq
Jan	-2.584938	0.919563	-1.086563	-1.520313	-0.385188	2.021438	-0.10325	-2.692625	0.489875	-2.7285	-0.847438	3.235813	-2.77125	5.00825	-3.02675	-1.799125
Feb	0.738	-0.623688	-1.251438	0.359188	0.159188	-0.635063	-3.114938	-1.687313	2.445125	-1.152313	-2.489375	1.431875	-1.374938	-0.097125	-2.725625	-1.197438
Mar	-1.600625	-1.423063	-3.258063	3.292625	0.886688	3.488063	-1.817938	10.0165	1.238938	-1.826688	-1.228125	0.13025	-2.601375	0.288063	-2.561375	0.673313
Apr	-2.574313	-2.005563	-4.71325	3.85825	0.871938	-1.107875	-2.308188	-1.442563	0.502188	-3.687875	-1.201313	-2.031688	-1.956625	-2.262875	-2.678313	-2.238375
May	-0.62075	-2.766438	-2.927	-0.601375	-1.08	-0.15575	-2.669	-2.576938	0.087	-2.99875	-2.167688	-0.237625	-2.415313	-1.063875	-1.644438	-1.564375
Jun	-2.338188	-0.58175	-2.912188	-7.833188	-0.116813	1.55575	6.12825	-6.404625	-0.459063	-1.206563	-1.484125	0.786625	-1.632063	0.612813	-3.070875	0.614438
Jul	-0.87775	1.526375	1.022875	-1.928625	0.228688	-4.32925	0.239125	-2.901	1.914875	-3.047938	-1.314813	-1.13675	3.7445	-2.458875	-3.615188	4.395375
Aug	-0.906438	-3.379938	-1.16325	-9.523813	-0.63575	2.914938	1.615188	-2.444688	-1.381688	-0.165063	-3.669625	-2.509438	-5.0755	-1.198813	-3.442313	-1.194688
Sep	-2.418875	-0.717125	1.8325	-11.92331	1.369875	1.188188	0.929875	-2.515938	0.332125	-0.72275	-3.041813	-2.510938	-2.966	-4.024063	-2.843063	0.306063
Oct	2.488125	-0.883313	-1.472188	-5.633688	-0.713563	-0.050313	-2.583313	-0.896688	-0.214	-0.88575	-1.428063	2.563563	-3.447438	0.02175	-2.528813	-0.42975
Nov	0.063063	-2.317625	1.32425	-8.311125	0.914438	2.008313	1.42475	-1.969	-0.579438	1.297188	-1.048063	-0.23475	-4.926375	-0.107063	-2.7985	6.374
Dec	-1.472125	-3.197563	-4.77425	-4.597875	1.537688	-1.586938	-1.501125	2.147438	0.832813	0.209813	-0.173125	-2.576125	-2.828875	0.78725	-1.865063	0.025563

7.4.2. Monte-Carlo Simulation Results

In this simulation, the independent approach has been used because the correlation between water production (TWP) and its cost (TUC) is small, as discussed in section 7.1.1, hence, it can perform the simulation of each of them independently. The historical data for TUC and TWP have been replicated 100 times by using the Monte Carlo simulation independently. The Thomas-Fiering time series model was used to generate 100 replicates of the monthly TWP and TUC. To assess the performance of the stochastic model, important statistical parameters (mean, standard deviation, serial correlation and skewness) of the historic were compared with the generated.

The full result of these comparisons are presented in Appendix F but Table 7-6 and Table 7-7 are examples of the results for the TUC for Yanbu 1 plant and the TWP for the Khobar 2 plant, respectively, from which it is clear that the Thomas-Fiering model has reproduced the parameters adequately. This evidence of the adequate performance of the stochastic model can be seen in Appendix F.

In most of the TWP and TUC generated monthly data, whiskers and box plot diagrams (Appendix G) are more symmetrical than those for historical data. Hence, the distribution for generated data has more normality than for historical data. As an example, the medians in TUC in the Shuqiq plant have shifted to the middle of box plot in most generated monthly values. In addition, the means are closer to the medians, which is very clear in February, April and May of TUC in Shuqiq plant case study (see Figures 7-7, 7-8). The whiskers in most TWP, and TUC generated data are longer than in the historical data, as shown in Appendix G. For example as it can be seen from Figures 7-9, 7-10, that most of the whiskers of the TWP generated data of the Jubail 1 plant are longer than in the historical data. This gives an indication that the maximum and minimum in generated data are wider apart than historical data. Nevertheless, there is a good match between generated and historical as shown in the statistical parameters comparison tables (Appendix G).

Table 7-6: Comparison of statistical parameters of total water production (TWP) of Kohbar 2 Plant

	Parameter	Plant	Jan	Feb	Mar	Apr	May	Jun
Historical, TWP	Mean	AK2	4933459.1	4434231.2	4654324.0	4518376.3	4663583.2	4457129.3
	SD	AK2	639604.0	596346.7	797508.4	699907.6	734325.0	860198.1
	Correlation	AK2	0.47	0.76	0.72	0.86	0.92	0.86
	Skew	AK2	-0.71	-0.36	-0.27	-0.42	-0.27	-0.53

	Parameter	Plant	Jul	Aug	Sep	Oct	Nov	Dec
Historical, TWP	Mean	AK2	4373187.2	4442263.0	4539613.2	4645810.8	4967354.2	5168424.3
	SD	AK2	969534.3	716866.6	631925.9	570701.4	558717.2	508077.2
	Correlation	AK2	0.81	0.96	0.58	0.73	0.68	0.59
	Skew	AK2	0.04	0.10	-0.64	0.45	0.21	0.49

	Parameter	Plant	Jan	Feb	Mar	Apr	May	Jun
Generated, TWP	Mean	AK2	4908173.0	4416760.0	4645217.7	4495711.8	4648140.6	4444152.1
	SD	AK2	684435.1	636357.6	814583.1	756845.8	758270.1	877471.9
	Correlation	AK2	**0.03**	0.78	0.72	0.86	0.91	0.86
	Skew	AK2	-1.00	-0.75	-0.44	-0.94	-0.48	-0.72

	Parameter	Plant	Jul	Aug	Sep	Oct	Nov	Dec
Generated, TWP	Mean	AK2	4390270.4	4456867.2	4552306.2	4672626.9	4965124.8	5214234.9
	SD	AK2	977336.3	739902.9	689024.2	612753.1	605212.2	728690.7
	Correlation	AK2	0.82	0.96	0.55	0.68	0.64	0.41
	Skew	AK2	0.17	0.30	-1.45	0.58	0.44	2.45

Table 7-7: Comparison of statistical parameters of total water production (TUC) of Yanbu 1 Plant.

	Parameter	Plant	Jan	Feb	Mar	Apr	May	Jun
Historical, TWP	Mean	Yan1	4.4239	5.0586	4.7799	4.9677	4.7284	4.8116
	SD	Yan1	0.6041	0.6775	0.6749	0.5874	0.5104	0.5684
	Correlation	Yan1	-0.6549	0.6222	0.4603	0.6662	0.1730	0.5319
	Skew	Yan1	-0.3098	0.3814	-0.6262	0.7165	0.1885	-0.2287

	Parameter	Plant	Jul	Aug	Sep	Oct	Nov	Dec
Historical, TWP	Mean	Yan1	4.7694	4.6279	4.6747	4.2407	4.4323	5.2592
	SD	Yan1	0.7145	0.3716	0.5467	0.5524	0.4939	1.1073
	Correlation	Yan1	0.6878	0.7058	0.5534	0.5703	0.4830	0.4934
	Skew	Yan1	1.1406	-0.3875	-0.0868	0.1632	-0.3515	1.1959

	Parameter	Plant	Jan	Feb	Mar	Apr	May	Jun
Generated, TWP	Mean	Yan1	4.4251	5.0826	4.7783	4.9828	4.7330	4.7898
	SD	Yan1	0.5990	0.7088	0.7320	0.5883	0.5430	0.5784
	Correlation	Yan1	-0.0306	0.6319	0.4714	0.6968	0.0976	0.5224
	Skew	Yan1	-0.6601	0.7784	-1.3265	0.7054	0.4143	-0.3290

	Parameter	Plant	Jul	Aug	Sep	Oct	Nov	Dec
Generated, TWP	Mean	Yan1	4.7461	4.6089	4.6807	4.2572	4.4410	5.3250
	SD	Yan1	0.7900	0.3743	0.5342	0.5513	0.4997	1.2000
	Correlation	Yan1	0.6001	0.6016	0.5708	0.5599	0.4685	0.5568
	Skew	Yan1	3.1827	-0.6171	0.0305	0.5191	-0.4066	1.8016

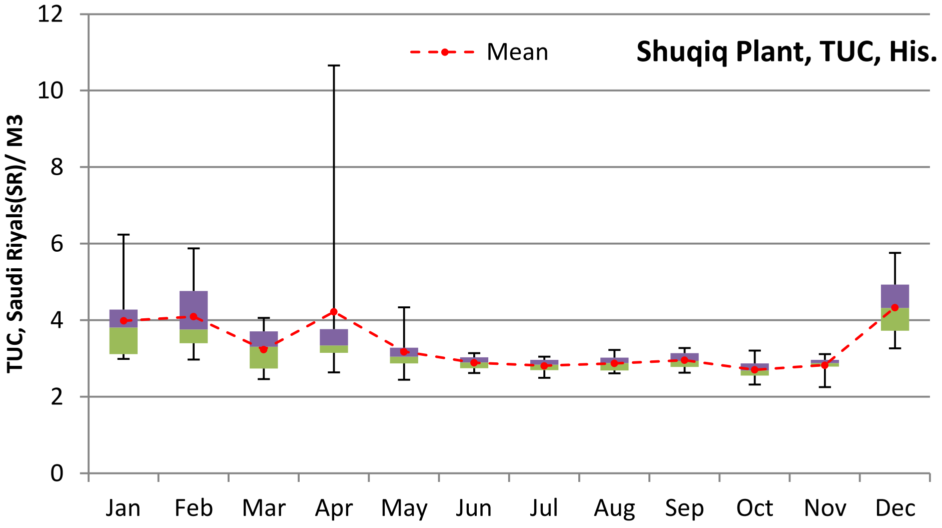

Figure 7-7: Whiskers and box plot diagram of total unit cost of historical data of Shuqiq plant

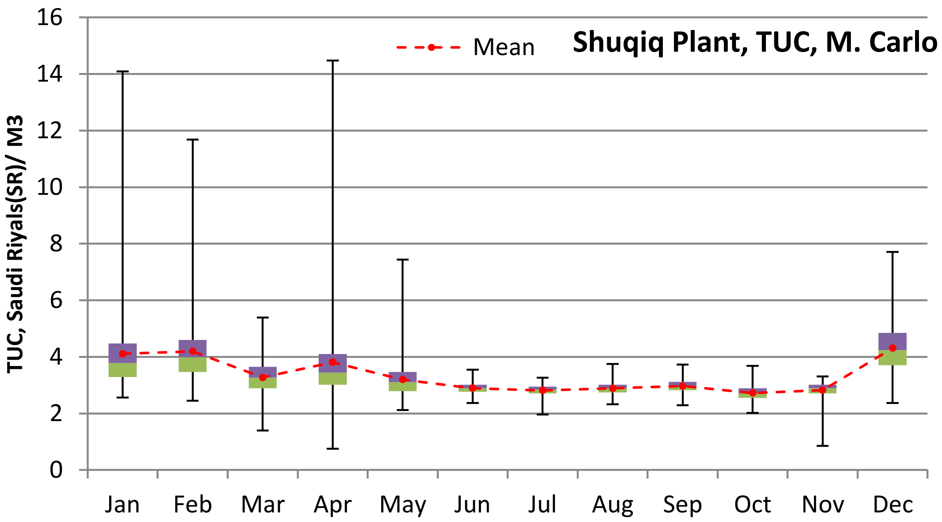

Figure 7-8: Whiskers and box plot diagram of total unit cost of the generated data by Monte Carlo of Shuqiq plant.

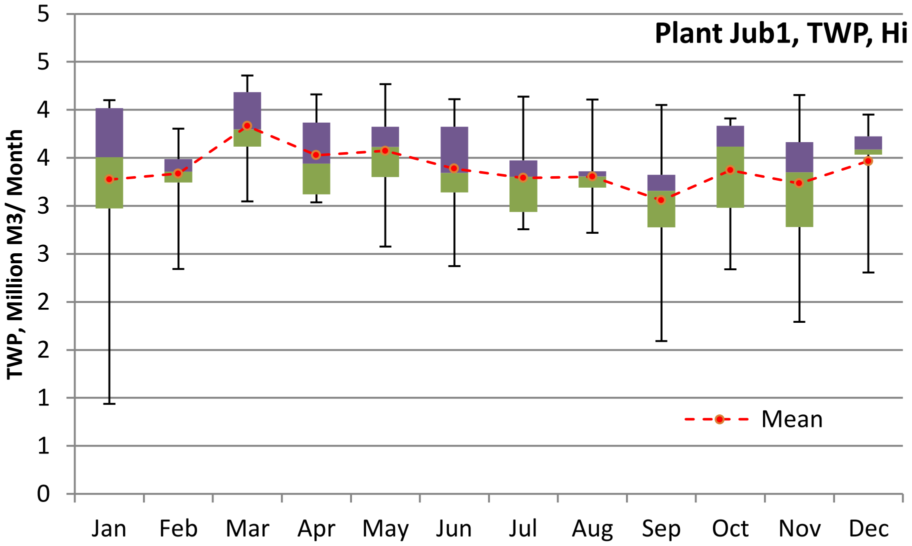

Figure 7-9: Whiskers and box plot diagram of total water production of historical data of Jubail 1 plant.

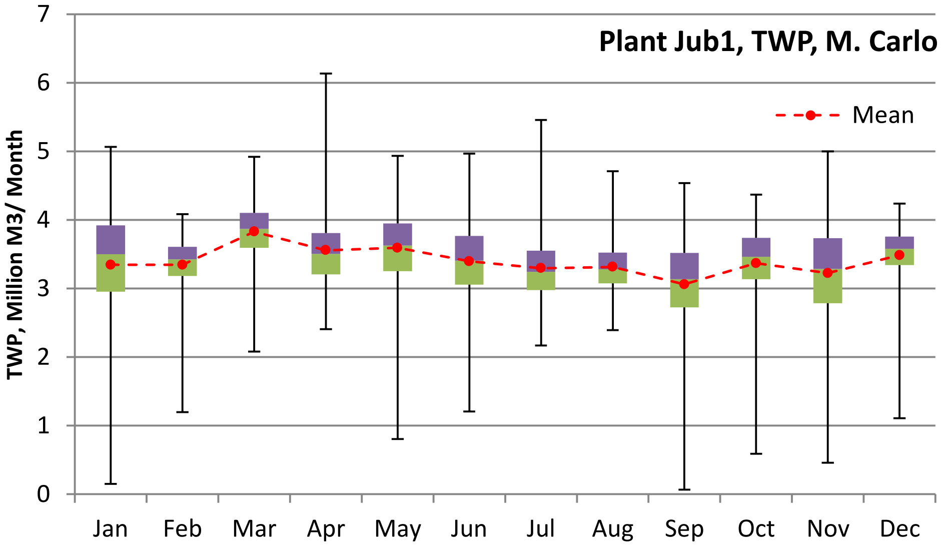

Figure 7-10: Whiskers and box plot diagram of total water production of the generated data by Monte Carlo of Jubail 1 plant.

7.4.3. Population of prediction models

Separate regression models were calibrated for each of replicate pair for TWP and TUC, thus providing 100 equally likely models for each regression type or formulation. The slopes and constants of the 100 stochastic models of Power, Inverse, and Logarithmic equations are presented in Table 7-9, Table 7-10, and Table 7-11 respectively.

As discussed in section 3.4.6, the mean model of the 100 stochastic models is the average of constants and slope values of these models. The mean and standard deviation of the constant and slope values of each group of equations are presented in Table 7-8. Therefore, the final models of Logarithmic, Inverse, and Power are presented in equations (7-9), (7-10), and (7-11) respectively.

Table 7-8: Mean and standard deviation of the models of the generated data

Postulated model	Constant average (Mean)	Slope average (Mean)	Constant , Stander deviation,	Slope, Standard deviation
Power	109.376	-0.222 (exponent)	21.235	0.013
Inverse	3.771	927254.812	0.302	769971.140
Logarithmic	19.047	-0.988	0.803	0.052

Logarithmic $TUC = 19.04 - 0.988\,(\ln P)$ (7-9)

Inverse $TUC = 3.77 + (927254.8/P)$ (7-10)

Power $TUC = 109.3764 * P^{-0.22211}$ (7-11)

where TUC is the total unit cost (Saudi Riyals per metre cube) and P is the total water production (metre cube per month).

Table 7-9: Power equations of the 100 replicate stochastic models

Run NO.	Constant (a)	Slope (Exponent) (b)	Run NO.	Constant (a)	Slope (Exponent) (b)	Run NO.	Constant (a)	Slope (Exponent) (b)
1	94.23	-0.21	***35***	125.33	-0.23	***69***	113.07	-0.22
2	105.24	-0.22	***36***	120.7	-0.23	***70***	86.12	-0.21
3	133.63	-0.24	***37***	117.81	-0.23	***71***	113.59	-0.22
4	104	-0.22	***38***	96.96	-0.22	***72***	130.05	-0.23
5	115.76	-0.23	***39***	98	-0.22	***73***	101.39	-0.22
6	120.89	-0.23	***40***	113.39	-0.23	***74***	84.99	-0.21
7	89.39	-0.21	***41***	84.21	-0.21	***75***	92.33	-0.21
8	103.07	-0.22	***42***	95.49	-0.22	***76***	87.43	-0.21
9	90.6	-0.21	***43***	98.11	-0.22	***77***	95.69	-0.21
10	95.53	-0.22	***44***	105.09	-0.22	***78***	98.53	-0.22
11	113.17	-0.22	***45***	108.85	-0.22	***79***	91.56	-0.21
12	64.33	-0.19	***46***	133.89	-0.24	***80***	118.55	-0.23
13	84.6	-0.21	***47***	158.63	-0.25	***81***	118.02	-0.23
14	125.21	-0.23	***48***	109.67	-0.22	***82***	116.66	-0.23
15	128.38	-0.23	***49***	152.66	-0.24	***83***	106.1	-0.22
16	137.91	-0.24	***50***	125.06	-0.23	***84***	110.7	-0.22
17	80.41	-0.2	***51***	97.9	-0.22	***85***	121.05	-0.23
18	78.15	-0.2	***52***	138.71	-0.24	***86***	95.55	-0.21
19	86.03	-0.21	***53***	126.16	-0.23	***87***	98.34	-0.21
20	94.46	-0.21	***54***	98.83	-0.22	***88***	168.02	-0.25
21	127.95	-0.23	***55***	101.81	-0.22	***89***	90.23	-0.21
22	90.09	-0.21	***56***	88.37	-0.21	***90***	112.02	-0.22
23	129.59	-0.23	***57***	129.85	-0.24	***91***	105.13	-0.22
24	107.62	-0.22	***58***	78.8	-0.2	***92***	140.82	-0.24
25	93.95	-0.21	***59***	111.88	-0.22	***93***	107.17	-0.22
26	101.48	-0.22	***60***	112.85	-0.23	***94***	131.53	-0.24
27	94.46	-0.21	***61***	118.17	-0.23	***95***	140.44	-0.24
28	88.32	-0.21	***62***	96.16	-0.22	***96***	131.55	-0.24
29	162.76	-0.25	***63***	96.48	-0.21	***97***	80.39	-0.2
30	66.69	-0.19	***64***	123.85	-0.23	***98***	121.53	-0.23
31	91.83	-0.21	***65***	122.03	-0.23	***99***	113.92	-0.23
32	108.39	-0.22	***66***	102.01	-0.22	***100***	132.09	-0.24
33	82.86	-0.2	***67***	117.51	-0.23			
34	92.78	-0.21	***68***	179.01	-0.26			

Table 7-10: Inverse equations of the 100 replicate stochastic models

Run NO.	Constant (a)	Slope (b)	Run NO.	Constant (a)	Slope (b)	Run NO.	Constant (a)	Slope (b)
1	4.01	2E+05	***35***	3.76	8E+05	***69***	3.76	1E+06
2	4.01	4E+05	***36***	3.78	1E+06	***70***	3.97	4E+05
3	3.44	2E+06	***37***	3.79	9E+05	***71***	3.66	1E+06
4	3.48	2E+06	***38***	3.94	5E+05	***72***	3.5	2E+06
5	3.43	2E+06	***39***	3.72	1E+06	***73***	3.93	5E+05
6	3.17	2E+06	***40***	3.18	2E+06	***74***	4.01	2E+05
7	3.94	5E+05	***41***	4.04	1E+05	***75***	3.92	5E+05
8	3.98	4E+05	***42***	3.41	2E+06	***76***	4.05	2E+05
9	4.03	3E+05	***43***	3.67	1E+06	***77***	3.63	1E+06
10	3.69	9E+05	***44***	4.13	1177	***78***	3.66	1E+06
11	4.18	83300	***45***	3.38	2E+06	***79***	3.8	8E+05
12	4.16	4244	***46***	4.06	2E+05	***80***	3.62	1E+06
13	3.73	1E+06	***47***	3.18	2E+06	***81***	3.82	6E+05
14	3.57	1E+06	***48***	4.02	80832	***82***	3.3	2E+06
15	4	4E+05	***49***	3.03	3E+06	***83***	3.46	2E+06
16	3.82	8E+05	***50***	3.27	2E+06	***84***	3.99	5E+05
17	3.96	7E+05	***51***	4.13	39916	***85***	3.98	3E+05
18	3.36	2E+06	***52***	3.06	3E+06	***86***	3.87	6E+05
19	3.73	1E+06	***53***	3.64	1E+06	***87***	3.61	2E+06
20	4.16	1E+05	***54***	3.33	2E+06	***88***	3.6	1E+06
21	3.51	2E+06	***55***	4.08	13821	***89***	4.13	66638
22	3.52	2E+06	***56***	4.15	1960	***90***	3.87	7E+05
23	3.77	9E+05	***57***	4.09	42434	***91***	4.16	325.6
24	3.97	2E+05	***58***	3.85	6E+05	***92***	3.65	1E+06
25	3.65	1E+06	***59***	3.54	2E+06	***93***	3.43	2E+06
26	3.88	7E+05	***60***	3.72	1E+06	***94***	4.13	67194
27	3.98	4E+05	***61***	3.14	2E+06	***95***	3.3	2E+06
28	4.08	93071	***62***	4.11	572.2	***96***	3.36	2E+06
29	4.2	1E+05	***63***	4.17	24750	***97***	4.07	50560
30	3.9	5E+05	***64***	4.02	4E+05	***98***	3.75	1E+06
31	3.89	6E+05	***65***	4.07	2E+05	***99***	4.05	1E+05
32	3.73	1E+06	***66***	4.1	3E+05	***100***	3.86	7E+05
33	3.77	9E+05	***67***	3.89	5E+05			
34	4.15	32355	***68***	3.21	2E+06			

Table 7-11: Logarithmic equations of the 100 replicate stochastic models

Run NO.	Constant (a)	Slope (b)	Run NO.	Constant (a)	Slope (b)	Run NO.	Constant (a)	Slope (b)
1	18.18	-0.93	***35***	19.19	-1	***69***	19.4	-1.01
2	19.41	-1.01	***36***	19.65	-1.02	***70***	17.89	-0.91
3	19.56	-1.02	***37***	19.37	-1.01	***71***	19.37	-1
4	18.7	-0.96	***38***	19.01	-0.99	***72***	19.6	-1.02
5	19.09	-0.99	***39***	18.6	-0.96	***73***	18.91	-0.98
6	19.2	-1	***40***	19.53	-1.02	***74***	18.33	-0.95
7	18.1	-0.93	***41***	18.23	-0.94	***75***	18.43	-0.95
8	19.05	-0.99	***42***	18.55	-0.96	***76***	18.09	-0.92
9	18.2	-0.93	***43***	18.62	-0.96	***77***	18.53	-0.95
10	18.05	-0.93	***44***	19.25	-1	***78***	18.92	-0.98
11	19.65	-1.02	***45***	19.05	-0.99	***79***	18.18	-0.93
12	17.24	-0.87	***46***	19.94	-1.05	***80***	19.31	-1
13	18.51	-0.95	***47***	20.2	-1.06	***81***	19.02	-0.99
14	19.84	-1.04	***48***	18.53	-0.96	***82***	19.16	-1
15	19.71	-1.03	***49***	21.08	-1.12	***83***	19.36	-1.01
16	19.86	-1.04	***50***	19.52	-1.01	***84***	19.14	-0.99
17	18.51	-0.94	***51***	18.78	-0.97	***85***	19.69	-1.03
18	18.3	-0.94	***52***	20.43	-1.08	***86***	18.27	-0.94
19	18.09	-0.93	***53***	19.8	-1.03	***87***	19.05	-0.98
20	18.71	-0.96	***54***	19.11	-0.99	***88***	20.88	-1.11
21	20.16	-1.06	***55***	18.72	-0.97	***89***	18.35	-0.94
22	18.4	-0.94	***56***	18.45	-0.95	***90***	19.2	-1
23	19.51	-1.02	***57***	19.62	-1.03	***91***	19.19	-1
24	18.95	-0.99	***58***	17.59	-0.89	***92***	19.88	-1.04
25	17.82	-0.91	***59***	19.36	-1	***93***	18.81	-0.98
26	19.05	-0.99	***60***	19.01	-0.99	***94***	20.18	-1.06
27	18.35	-0.94	***61***	19.17	-1	***95***	19.75	-1.03
28	17.78	-0.91	***62***	18.27	-0.94	***96***	20.25	-1.07
29	21.09	-1.11	***63***	18.19	-0.93	***97***	20.25	-1.07
30	17.2	-0.87	***64***	19.99	-1.05	***98***	17.34	-0.88
31	18.91	-0.98	***65***	19.44	-1.01	***99***	19.07	-0.99
32	19.04	-0.98	***66***	19.22	-0.99	***100***	19.61	-1.03
33	18.3	-0.94	***67***	19.16	-1			
34	18.47	-0.95	***68***	20.84	-1.11			

7.4.4. Confidence intervals of prediction models

The 95% confidence limits for the parameters of the calibrated models obtain using equations (3-23, 3-24) are shown in Table 7-12. Using thse values and the mean parameter values in Table 7-8, the mean and 95% limits of the prediction models are compared in Figures 7-9 to 7-11 for the power, logarithmic and inverse models respectively. Also superimposed on the ppts is the model based on the historical data.

For the three models, the mean of the stochastic models is almost indistinguishable from the historical model which is a further proof of the adequacy of the stochastic generation model.

As far as the confidence limits are concerned, the power model has the widest interval, making it the least reliable of all the three models for prediction purposes, in terms of confidence limits. This is particularly true at low production capacity but as production capacity increases, the interval of the predicted cost narrows.

Table 7-12: Confidence interval limits of the logarithmic, inverse, and power stochastic models

Postulated model	Upper limit, 95% confidence interval of the Constant values	Lower limit, 95% confidence interval of the Constant values	Upper limit¸ 95% confidence interval of the Slope values	Lower limit¸ 95% confidence interval of the Slope values
Power	150.997	67.755	-0.197	-0.247
Inverse	4.361	3.181	2429915.085	-575405.462
Logarithmic	20.622	17.472	-0.886	-1.090

The confidence interval of the logarithmic is almost as wide as that of the power model, which also means that its prediction is too noisy for effective decision making. Apart from this, however, the limits of the logarithmic model is constantly widening, and as seen in Figure 7-12, the lower limit actually becomes negative after the production capacity of $10Mm^3$ and remains so thereafter. Negative production cost is implausible and thus the logarithmic model cannot be justified as a valid model for the cost prediction. On the other hand, the power and logarithmic models give a better fit with the mean.

The appeal of the inverse model is apparent from Figure 7-13, because its limits are the narrowest of all the three models, even though there is a reduction in unit cost at the lower limit of inverse model as production decreases and a poorest fit of the mean in the Inverse model. The evidence in Figure 7-13 is well supported by the calibration results presented in Table 7-7, where the inverse model has the highest R2 of all the models tested.

On this basis, the inverse model has been selected as the model for the prediction of the monthly cost of desalination in Saudi Arabia. The relevant model equations are:

Historical Cost Model	$TUC = 2.76 + (3643116.36/P)$	(7-7)
95% Upper limit Cost Model	$TUC = 4.361 + (2429915.085/P)$	(7-12)
95% Lower limit Cost Model	$TUC = 3.181 + (-575405.462/P)$	(7-13)

Although, this model is an empirical model, like the previous prediction models discussed in section 2.4.6, the current developed model relies for its calibration on data collected from Saudi Arabia, whereas the previous models rely for their calibration on data collected from specific countries, and are thus unlikely to be applicable in countries with different socio-economic and other situations. To illustrate this, two of the existing models – Zhou and Tol (2005, eq.2-13) and Limei et al. (2008, Eq. 2-15) that also used total production as the explanatory variable were applied to the Saudi Arabia data used in the current study. The resulting scatter plots are shown in Figure 7-14 from where it is clear that both models significantly under predict the Saudi production cost. The Zhou and Tol (2005) model (Figure 7-14 (c)) is particularly poor and shows no sensitivity at all to total water production, which is unlikely to the case. The currently developed model is shown in Figure 7-14 (a) from where its superiority to the two existing cost models is apparent. The need to develop a separate model for Saudi Arabia situation was emphasised earlier on in this thesis and the information in Figure 7-14 has lend further support to the argument that existing models that were calibrated using data from other regions may not perform well for Saudi Arabia. Such models are therefore unlikely to be useful tools for operational decision making as far as sea water desalination plants in Saudi Arabia is concerned.

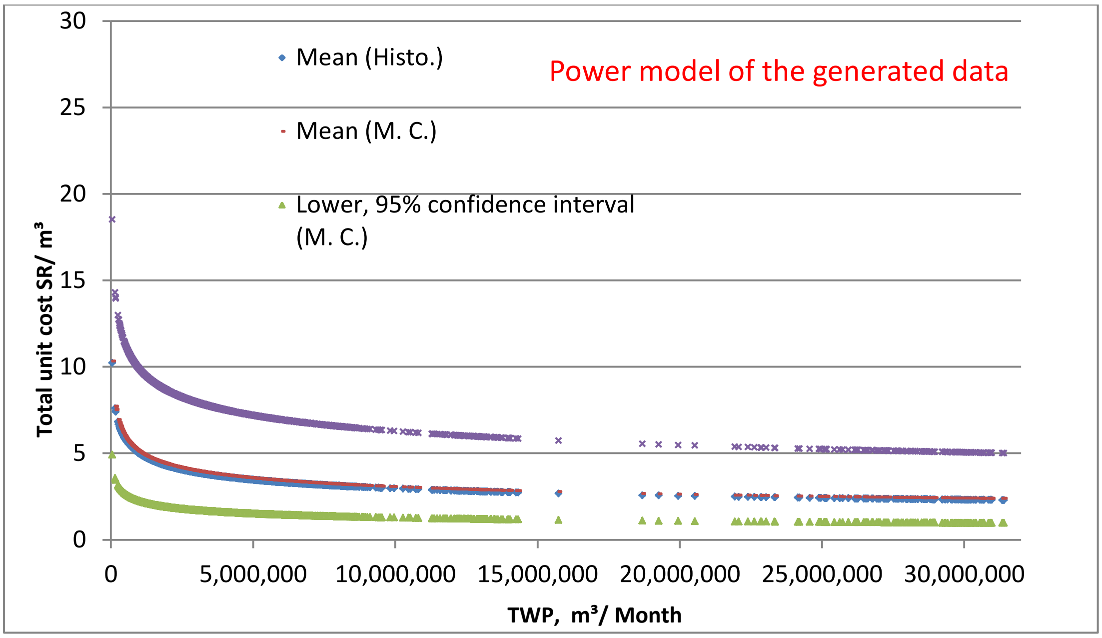

Figure 7-11: Diagram of final power model with 95% confidence interval limits and compared with the historical model.

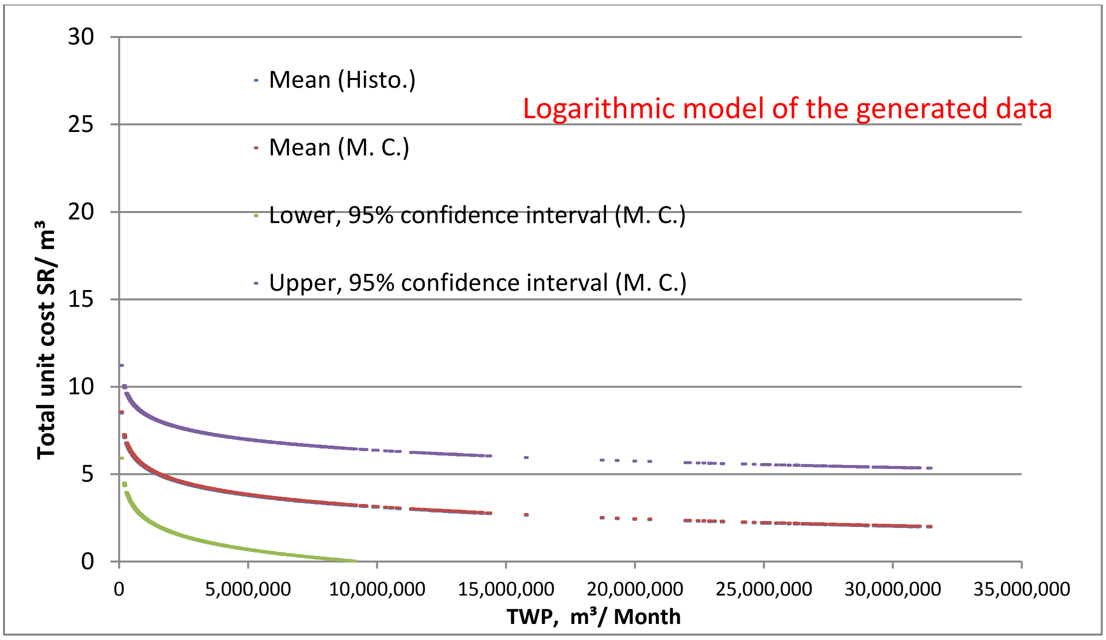

Figure 7-12: Diagram of final logarithmic model with 95% confidence interval limits and compared with historical model.

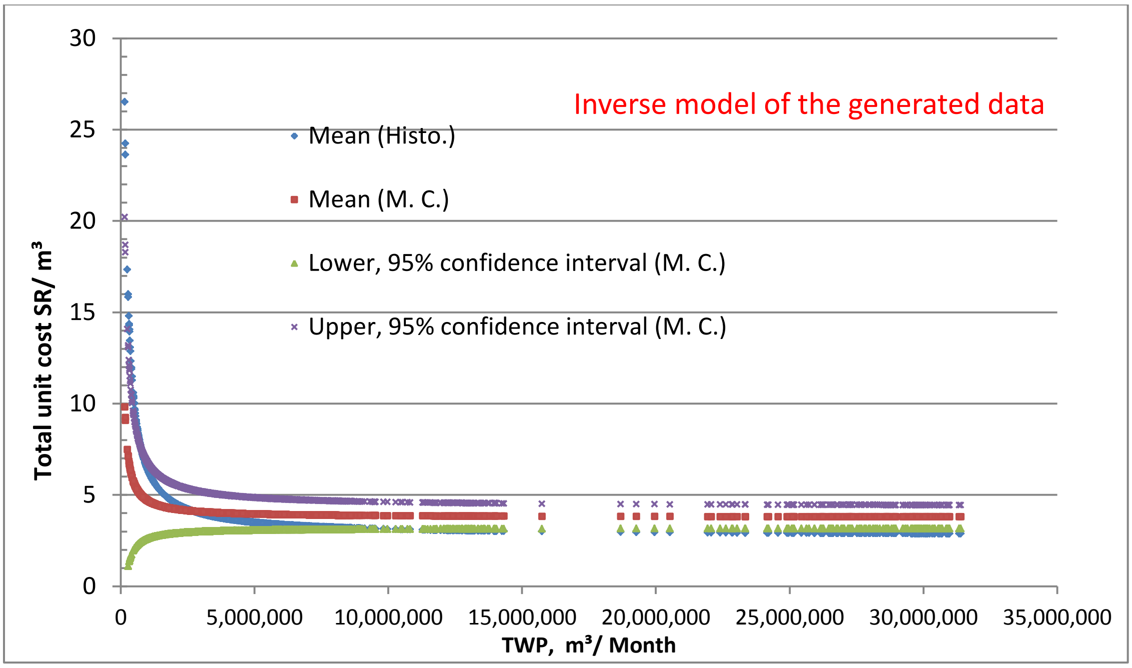

Figure 7-13: Diagram of final inverse model with 95% confidence interval limits and compared with historical model.

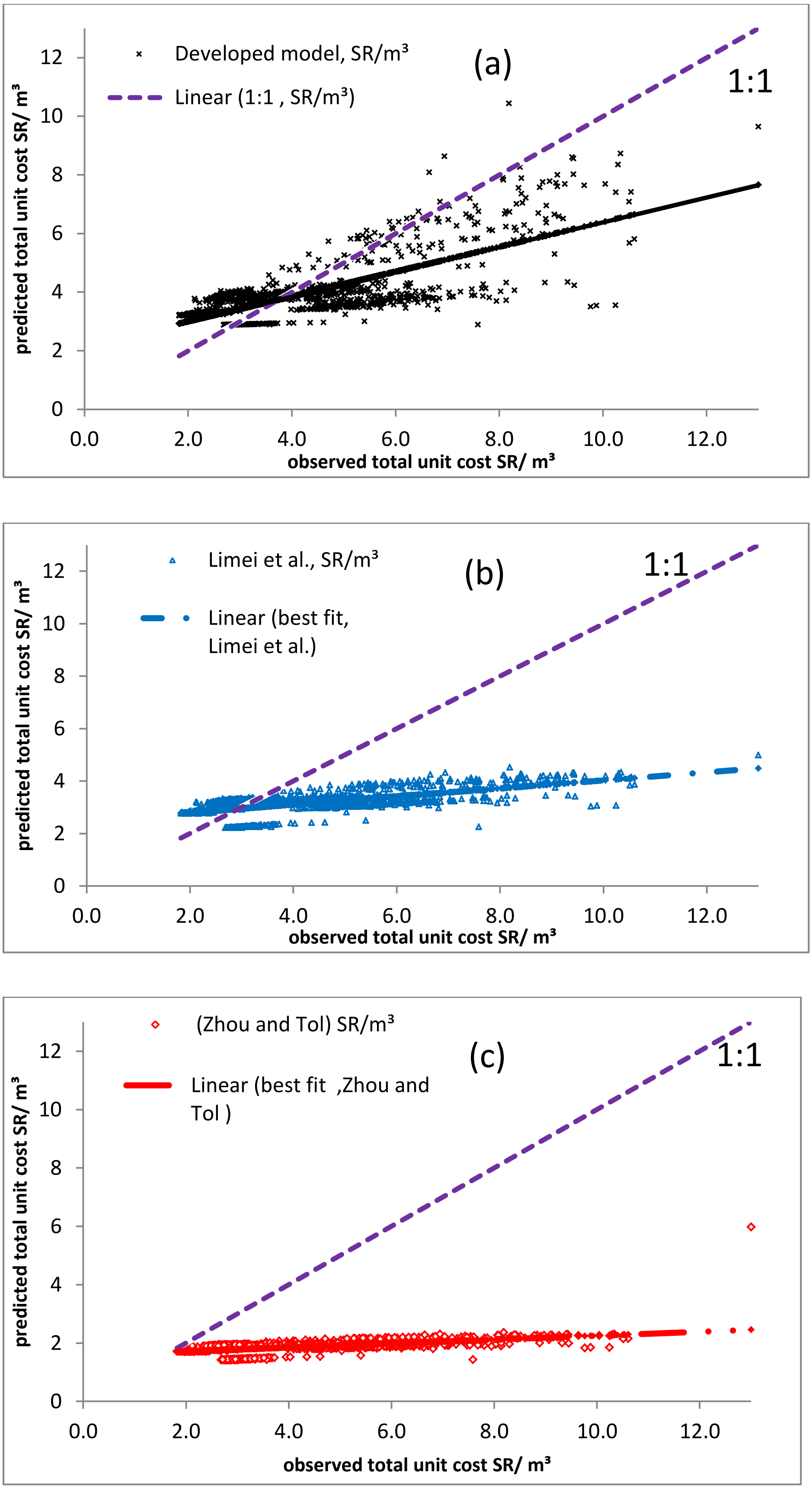

Figure 7-14: X-Y scatter plot to compare results between developed model (a) and Limei et al. (b), and Zhou and Tol (c).

7.5. Summary

Different factors play a role in determining the cost of water production from sea water desalination plants. Therefore, an exploratory correlation was carried out, with a view to identify those factors that are statistically significant for the production cost in Saudi Arabia. As a conclusion of this study, it can be said that there is a reasonable relationship between total water production and total unit cost. In contrast, there is a relatively lower correlation between water production unit cost and energy consumption, product water TDS, and desalination techniques. Moreover, there was not a relationship between seawater TDS and total unit cost.

The best correlation with monthly total unit cost is the total water production. So, this research has considered two variables: production cost and water production. As a consequence, total water production has been used to create a predictive model of the cost of fresh water produced from seawater desalination plants in Saudi Arabia.

To construct the uncertainty bounds of the models a Monte-Carlo simulation approach was used. This employed the Thomas-Fiering seasonal hydrologic model to replicate the historic record. The different regression models for predicting the production cost using water production as explanatory variable were calibrated for each replicate and used to construct confidence limits. As a final conclusion of the Monte-Carlo simulation analyses the inverse model proved to be the most reliable for predicting the cost of production, using the total water production as the independent variable. The final mean model results are very close to the historical values, the upper and lower 95% limits are narrow both of which at least to the adequacy of the stochastic model and the reliability of the prediction equation for decision making.

Chapter 8 - Conclusion and Recommendation

8.1. Conclusions

In concluding this thesis, it is pertinent to review its objectives and evaluate the extent to which they have been met. The objectives as set out in Chapter 1 were:

i. Review the water resource situation and its management in Saudi Arabia.
ii. Review different desalination techniques being applied both in Saudi Arabia and internationally, and identify the key factors that affect their production cost.
iii. Collect data (capacity, cost history, type of technology, raw water quality, etc.) on existing seawater desalination plants in Saudi Arabia.
iv. Carry out an exploratory correlation analysis with a view to identifying those factors which are statistically significant for the production cost.
v. Formulate, calibrate and validate different regression models for predicting the production cost, using the identified factors as explanatory variables.
vi. Carry out sensitivity studies on the developed models and make recommendations as to their utility for prediction.
vii. Develop a Monte Carlo simulation approach to characterise the uncertainty limits of the developed models.

The first objective was achieved in Chapter 2 which contains a review of water resources, water demand, and water management institutions in Saudi Arabia. The significance of sea water desalination plants in the water supply situation in Saudi Arabia was described in detail. The costs of water production from seawater desalination plants and factors affecting the cost of production from desalination plants were also reviewed. Finally a review of predictive models of the cost of water from desalination plants that have been developed in previous studies was presented.

Data collection formed an important aspect of the work without which the development of the models could not occur. Thus, details of the collected data are presented in Chapter 3. Generally, forecast budgets are based on monthly cash budget forecasting. Therefore, monthly data relating to water produced by seawater desalination plants in Saudi Arabia were collected from 16 desalination plants between the years 2001 and 2010. These include type of desalination technique, total water production, sea water salinity, product water salinity. Other variables were either missing or unavailable in the required monthly temporal scale and had to be derived. These include energy consumption per cubic metre of desalted water and total unit cost. The estimation of total unit cost involved estimating the monthly capital cost, taking into account the time value of money, and the missing values of monthly operating costs.

The development of the prediction model was achieved in Chapter 7. An exploratory correlation was carried out, with a view to identifying those factors that are statistically significant for the production cost in Saudi Arabia. The historical data for total water production were used to create a predictive model of the cost of fresh water produced from seawater desalination plants in Saudi Arabia. The models were formulated, calibrated and validated.

As an uncertainty assessment of model development, the historical data of total water production and total unit cost were replicated using Monte-Carlo simulation and the Thomas-Fiering time series model. This led to the development of uncertainty limits for the prediction model as reported in Chapter 7.

From the above, it is clear that all the objectives set out in Chapter 1 for this study have been achieved. From the entire study, the following specific conclusions were obtained:

8.1.1. 8.1.1. There is a limited conventional water resource in Saudi Arabia. There are no rivers or lakes, while the total amount of runoff is only 5 billion cubic metres per year and the annual average consumption is more than 13.5 billion cubic metres. This limitation in conventional water resource means the country is thus forced to use sea water desalination plants to cover the shortage in drinking water. The increasing water demand, owing to the acceleration of Saudi population growth, is resulting in the construction of new desalination plants. The problem with this method, however, is the high cost of desalted water from these plants. To fully understand the factors that contribute to desalination costs, which could then be used to develop appropriate models for predicting costs that can support budgeting and/or cost reductions in decision making, this case study has investigated the development of such models for predicting monthly production costs using data from 16 operational plants in Saudi Arabia.

8.1.2. The annual capital cost of seawater desalination plants has been estimated based on the opportunity cost value. The equivalent annual cost (EAC) method is suitable to account for the annual capital cost in such research, where there are different desalination plants with different start times, as well as to evaluate non-profit projects. As the desalination plants used in the research are public projects with a 30 year life cycle, the rate of return applied for calculating the EAC is the U.S. treasury yield percentage applied at the first year of the life cycle of each plant.

8.1.3. The shortness of economic data in Saudi Arabia means that every effort must be devised to increase the data record length so as to reduce the prediction uncertainty of the developed models. In the case study plants, the required monthly costs were only available for a short period whereas annual costs exist for a much longer period; disaggregating these annual cost data to monthly provided the much needed lengthening of the monthly cost data for model development. The method of fragments that has been so successfully used in stochastic hydrology studies for disaggregating annual runoff to monthly runoff was employed in the study for the disaggregation. Extensive tests later carried out showed that this approach provided reliable disaggregation of the annual cost data. As far as the author is aware, this is the first of such an application in economic and financial investigation.

8.1.4. There was a significant difference in the energy consumption between RO and MSF desalination plants, with the MSF technique consuming (18.7 kwh/ m^3), which is more than double the energy of the RO technique (8.1 kwh/m^3), the electrical power consumption accounted for a considerable part (28.3%) of the total energy consumption at MSF desalination plants. This is in line with what is expected between these two technologies. However, despite the energy intensive nature of MSF, it is still the preferred method because of its versatility and ability to cope with a high range of salinity and other feed-water quality characteristics. This is why 12 of the 16 case study plants use MSF while only 4 use RO. On international scale, i.e. considering areas outside the Gulf States, the RO is more popular principally because of the moderate salinity of the feed water in those regions. For example, the average TDS in Gulf states area is 48,000 ppm whereas in the rest of the world where RO is more widely used, average TDS is < 36,000 ppm.

8.1.5. On the basis of the correlation study, it can be said that there is a reasonable relationship between total water production and total unit cost at correlation coefficient -0.303. In contrast, there is a relatively lower correlation between water production unit cost and energy consumption, product water TDS, and desalination techniques, where the correlation coefficients were 0.275, 0.157, and -0.136, respectively. Moreover, there was no relationship between seawater TDS and total unit cost.

8.1.6. Both the energy consumption and total water production are qualified to be used as independent variables in the cost prediction model. However, for this to happen, both the energy consumption and total water production must not be significantly correlated, which not the case in the result in correlation study as is mentioned above. Thus, only one of the two variables can be used in the prediction and the decision was therefore taken to use the variable that has best correlation with monthly total unit cost and is also commonly available. As noted previously, energy consumption data is not available for all the plants in Saudi Arabia; indeed, data on energy were only available for RO plants, while the consumption for the other desalination technologies had to be derived from first principles. Consequently, the study employed total water production as the lone predictor variable for the model of the cost of water produced from seawater desalination plants in Saudi Arabia. However, the model identification procedure is sufficiently generic and could readily be adapted in other situations where different independent variables are found to be more significant.

8.1.7. Based on the performance evaluation of the regression prediction models, the non-linear models (inverse, logarithmic and power) outperformed the linear model formulation. Of the three non-linear models, the inverse model produced the best performance, at coefficient of determination (R^2) 0.281.

8.1.8. The Monte-Carlo simulation carried out to quantify the uncertainty limits showed that the inverse model provides the narrowest limits, further confirming the superiority of this model formulation when compared to the power and the logarithmic models. The logarithmic model produced implausible (i.e. negative) limits while the limits of the power model were very wide, especially at low production capacities. For these reasons, the inverse model has been selected as the model for the prediction of the monthly cost of desalination in Saudi Arabia, despite the fact that the power and logarithmic models give a better fit with the mean.

8.2. Recommendations for further research

Despite the achievements recorded in this study, there are certain aspects which have been identified that would benefit from further investigation. However, if more time were available in the current research, the time value of money of the capital cost would be estimated at an average of interest rate for all desalination plants as an alternative way of capital cost estimation. Therefore, the following are suggested as areas for further work:

8.2.1. The current research focused on the factors that determine total unit cost of water production at desalination plants in Saudi Arabia and use these to develop a predictive model of production cost which is a big achievement. However, the study would be more useful if the different costs such as fuel, electricity, staff, chemicals, spare parts, utilities expenses such as security, and information technology (IT), plant administration, and insurance in the current research are studied individually

8.2.2. Many new sea water desalination plants have been constructed in last few years. It would be more appropriate if the cost of water produced from these plants and its correlation with other variables are studied.

8.2.3. The high inflation rate in recent years which has led to an increase in the cost of the spare parts, chemicals, and labour. Therefore, it would be useful if the data for more recent years, were added to the current study data and used to develop a predictive model based on data from 2001-2013. In any case, it would be necessary to re-assess the validity of the prediction model as more data become available in future years.

8.2.4. Many cities in Saudi Arabia that use seawater desalination plants to address the shortage of their supply of fresh water are non-coastal cities. For example, Riyadh (the capital city of Saudi Arabia) is combating its shortage of water from the Jubail plants, which are more than 400 kilometres, far away on the Arabian Gulf. The transfer of fresh water from sea water desalination plants to these non-coastal cities consumes a lot of money in pipeline construction and operations. Therefore, it would be valuable if the costs of water production and transportation were included in future studies.

8.2.5. Although, the current study includes the biggest 16 sea water desalination plants that produce 98% of the total water production in Saudi Arabia, there are many small sea desalination plants, which have not been included. It would be very useful if the factors affecting the cost of water were studied in these small plants and the results compared with the results of the current study.

8.2.6. The current study focused on certain factors that affect the cost of water production from sea water desalination plants. These factors have been used in the current research based on previous studies and data availability. However, there are other factors, such as plant age, plant location, that also affect the cost of water production and might be included in future studies.

8.2.7. Although the method of fragments have proved suitable for the disaggregation of annual to monthly costs, it would be more valuable if the current study was done with measured monthly operating costs. Thus, it is important that data collection efforts are better focused to ensure that data are collected at the right temporal scale. Additionally, the lack of comprehensive data on energy consumption should be addressed, given that energy cost dominates the total energy costs of desalination plants. The availability of these and other data will greatly assist any future work of a similar nature.

8.2.8 MSF uses more energy which because of the low, subsidised energy tariffs in Saudi Arabia has not translated to substantial monthly costs. However, energy consumption has a bearing on carbon footprint and climate change and so to better understand this linkage, it might be better to have predictive models of the energy consumption as a future research effort. The large discrepancy in the energy consumption between the three techniques, MSF, RO and MED means that such models must be technique-specific.

8.2.9 In this research study, cost models were lumped i.e. there was not distinction between the various techniques. This was possible for the case study because of the lack of any significant correlation between the type of plant and total unit cost. In regions where energy tariffs are higher than, and not subsidised as, in Saudi Arabia, this may not be the case. Additionally, the current case study was hindered by the lack of adequate economic data and any attempt to further separate the available data on the basis of desalination technique will only worsen the prediction uncertainty. However, a future research aimed at developing process specific cost function should be explored especially if the recommendation to intensify and improve the economic data is implemented.

References

A1-Sofi, M. A. K., & Srouji, M. M. (1995). Fuel allocation in dual-purpose plants. *Desalination*, *100*(1995), 65–70.

Abderrahman, W. a. (2000). Water Demand Management in Saudi Arabia. *The International Development Research Centre (IDRC)*, *16*(4), 465–473. doi:10.1080/713672529

Abderrahman, W. a. (2005). Groundwater Management for Sustainable Development of Urban and Rural Areas in Extremely Arid Regions: A Case Study. *International Journal of Water Resources Development*, *21*(3), 403–412. doi:10.1080/07900620500160735

ACWA. (2013). Shuaibah Water and Electricity Co. *ACWA Power International*. Retrieved November 04, 2013, from http://www.acwapower.com/about-us.html

Adeloye, A. J., Pal, S., & O'Neill, M. (2010). Generalised storage-yield-reliability modelling: Independent validation of the Vogel–Stedinger (V–S) model using a Monte Carlo simulation approach. *Journal of Hydrology*, *388*(3-4), 234–240. doi:10.1016/j.jhydrol.2010.04.043

Agashichev, S. P. (2004). Analysis of integrated co-generative schemes including MSF, RO and power generating systems (present value of expenses and "levelised" cost of water). *Desalination*, *164*(3), 281–302. doi:10.1016/S0011-9164(04)00196-1

Al-Ahmad, M., & Aleem, F. A. (1993). Scale formation and fouling problems effect on the performance of MSF and RO desalination plant in Saudi Arabia. *Desalination*, *93*(1-3), 287–310.

Alameddine, I., & El-Fadel, M. (2007). Brine discharge from desalination plants: a modeling approach to an optimized outfall design. *Desalination*, *214*(1-3), 241–260. doi:10.1016/j.desal.2006.02.103

Al-Basam, K. (2007). *Inflation in Saudi Arabia , Causes and Controls, a report to board of directors of Jeddah chamber of commerce and industry*. Jeddah. Retrieved from http://www.jcci.org.sa/Arabic/about/DocLib/تق.pdf

Aleqtisadiah. (2014, April 23). Ras al khair desalination plant. *Aleqtisadiah*. Dammam. Retrieved from http://www.aleqt.com/2014/04/23/article_843386.html

Alhedar, M. (2013, June). Kingdom maintains its position as the largest producer of desalinated water in the world. *Alriyadh*, p. 16419. Retrieved from http://www.alriyadh.com/2013/06/07/article841612.html

Al-Karaghouli, A., & Kazmerski, L. L. (2013). Energy consumption and water production cost of conventional and renewable-energy-powered desalination processes. *Renewable and Sustainable Energy Reviews*, *24*, 343–356. doi:10.1016/j.rser.2012.12.064

Alkolibi, F. M. (2002). POSSIBLE EFFECTS OF GLOBAL WARMING ON AGRICULTURE AND WATER RESOURCES IN SAUDI ARABIA : IMPACTS AND RESPONSES. *Springer*, *54*(1-2), 225–245.

Almuneef, M. a, Memish, Z. a, Balkhy, H. H., Alotaibi, B., Algoda, S., Abbas, M., & Alsubaie, S. (2004). Importance of screening household members of acute brucellosis cases in endemic areas. *Epidemiology and Infection, 132*(3), 533–40. Retrieved from http://www.pubmedcentral.nih.gov/articlerender.fcgi?artid=2870132&tool=pmcentrez&rendertype=abstract

Al-Mutaz, I. S., & Al-Namlah, A. M. (2004). Characteristics of dual purpose MSF desalination plants. *Desalination*, *166*, 287–294. doi:10.1016/j.desal.2004.06.083

Al-Qahtani, K., & Elkamel, a. (2009). Multisite Refinery and Petrochemical Network Design: Optimal Integration and Coordination. *Industrial & Engineering Chemistry Research*, *48*(2), 814–826. doi:10.1021/ie801001q

Al-Rasheed, M. (2010). *A History of Saudi Arabia* (2nd ed.). Cambridge: Cambridge University Press. doi:10.1017/CBO9780511993510

Al-Sahali, M., & Ettouney, H. (2007). Developments in thermal desalination processes: Design, energy, and costing aspects. *Desalination*, *214*(1-3), 227–240. doi:10.1016/j.desal.2006.08.020

Al-sofi, M. A. K., Hassan, A. M., Hamed, O. A., Dalvi, A. G. I., Kither, M. N. M., & Mustafa, G. M. (2000). Optimization of hybridized seawater desalination process, *131*(October), 147–156.

Al-Subaie, K. Z. (2007). Precise way to select a desalination technology. *Desalination*, *206*(1-3), 29–35. doi:10.1016/j.desal.2006.04.049

Aly, N. H., & El-fiqi, A. K. (2003). Thermal performance of seawater desalination systems, *158*(May), 127–142.

Al-Zubari, W. K. (2003). Exploiting Natural Resources. In *Exploiting Natural Resources*.

A-sofi, M. A. K. (2001). Seawater desalination SWCC experience and vision, *135*(November 2000), 121–139.

Avlonitis, S. a. (2002). Operational water cost and productivity improvements for small-size RO desalination plants. *Desalination*, *142*(3), 295–304. doi:10.1016/S0011-9164(02)00210-2

Azis, P. K. A., A-tisan, I., A-daili, M., Green, T. N., Dalvi, A. G. I., & Javeed, M. A. (2000). Effects of environment on source water for desalination plants on the eastern coast of Saudi Arabia, *132*(October), 3–6.

Baig, M. B., Aziz, A., & Kutbi, A. (1998). Design features of a 20 migd SWRO desalination plant , A1 Jubail , Saudi Arabia, *118*, 5–12.

Bank, W. (2014). Real interest rate (%). *Bank, World*. Retrieved August 01, 2014, from http://data.worldbank.org/indicator/FR.INR.RINR

BGFRS. (2012). Historical data for USA Finance, interest rate, 30-years. *Board of Governors of the Federal Reserve System, USA*. Retrieved October 12, 2012, from http://www.federalreserve.gov/releases/H15/data.htm#fn26

Blank, J. E., Tusel, G. F., & Nisanc, S. (2007). The real cost of desalted water and how to reduce it further. *Desalination*, *205*(1-3), 298–311. doi:10.1016/j.desal.2006.05.015

Borsani, R., & Rebagliati, S. (2005). Fundamentals and costing of MSF desalination plants and comparison with other technologies. *Desalination*, *182*(1-3), 29–37. doi:10.1016/j.desal.2005.03.007

Box, G., & Cox, D. (1964). An Analysis of Transformation. *Journal of Royal Statistical Society. Series B (Methodological)*, *26*(2), 211–252.

Brigham, E. F., & Ehrhardt, M. C. (2005). *Financial Managmnet, Theory and Practice*. (11th, Ed.). Mason, Ohaio, USA: South-Westren.

Buros, O. (2000). *The ABCs of desalting* (Second Edi.). Topsfield, Massachusetts, USA: International Desalination Association. Retrieved from http://www.miliarium.es/Desalinizador/The ABCs of Desalting.pdf

CDC. (2013). Cost Analysis. *Centers for Disease Control and Prevention, U.S. Department of Health & Human Services*. Retrieved November 17, 2013, from http://www.cdc.gov/owcd/eet/Cost/1.html

Chok, N. S. (2010). *PEARSON'S VERSUS SPEARMAN'S AND KENDALL'S CORRELATION COEFFICIENTS FOR CONTINUOUS DATA*. University of Pittsburgh. Retrieved from http://d-scholarship.pitt.edu/8056/

Chowdhury, S., & Al-Zahrani, M. (2013a). Characterizing water resources and trends of sector wise water consumptions in Saudi Arabia. *Journal of King Saud University - Engineering Sciences*. doi:10.1016/j.jksues.2013.02.002

Chowdhury, S., & Al-Zahrani, M. (2013b). Implications of Climate Change on Water Resources in Saudi Arabia. *Arabian Journal for Science and Engineering*, *38*(8), 1959–1971. doi:10.1007/s13369-013-0565-6

CIA. (2013). The World Factbook. *Central Intelligence Agency of USA*. Retrieved from https://www.cia.gov/library/publications/the-world-factbook/

Contreras, J., Espínola, R., Member, S., & Nogales, F. J. (2003). ARIMA Models to Predict Next-Day Electricity Prices, *18*(3), 1014–1020.

CSIS. (2011). Water and National Strength in Saudi Arabia. *Center for Strategic and International Studies*, (March).

Darwish, M. A., Al Asfour, F., & Al-Najem, N. (2002). Energy consumption in equivalent work by different desalting methods : case study for Kuwait. *Desalination*, *152*, 83–92.

Delorme, A. (2013). *Statistical methods* (pp. 1–23). San Diego California,. Retrieved from http://sccn.ucsd.edu/~arno/mypapers/statistics.pdf

Demiralp, S., & Yılmaz, K. (2012). Asymmetric response to monetary policy surprises at the long-end of the yield curve. *Journal of Macroeconomics*, *34*(2), 404–418. doi:10.1016/j.jmacro.2012.03.001

DER. (1991). *Guidelines for Preparation of Reuse Feasibility Studies for Applicants Having Responsibility for Wastewater Mana gement*. Florida. Retrieved from http://www.dep.state.fl.us/water/reuse/docs/reuse_final.pdf

Diciccio, T. J., & Efron, B. (1996). Bootstrap Confidence Intervals, *11*(3), 189–228.

DLMC. (2007). *Life Cycle Costing (LCC) as a contribution to sustainable construction: a common methodology*. *Final Report*. Retrieved from http://ec.europa.eu/enterprise/sectors/construction/files/compet/life_cycle_costing/guidance__case_study_en.pdf

DLR. (2007). *Concentrating Solar Power for Seawater Desalination*. Stuttgart. Retrieved from http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/aqua-csp/AQUA-CSP-Full-Report-Final.pdf

Dore, M. H. I. (2005). Forecasting the economic costs of desalination technology. *Desalination*, *172*(3), 207–214. doi:10.1016/j.desal.2004.07.036

Earl, D. J., & Deem, M. W. (2008). Monte Carlo simulations. *Methods in Molecular Biology (Clifton, N.J.)*, *443*, 25–36. doi:10.1007/978-1-59745-177-2_2

ECRA. (2013). About the Electricity & Co-Generation Regulatory Authority. *The Electricity & Co-Generation Regulatory Authority*. Retrieved from http://www.ecra.gov.sa/home.aspx

Edgell, H. S. (1992). Basement Tectonics of Saudi Arabia as Related to Oil Field Structures. *Proceedings of the International Conferences on Basement Tectonics*, *Volume 3*, pp 169–193.

EI. (2014). Water, Oil, Food – A Crisis for Saudi Arabia and the World. *The Earth Institute, Columbia University*. Retrieved from file:///F:/Wastewater/Agriculture water/22 Water, Oil, Food – A Crisis for Saudi Arabia and the World – State of the Planet.htm

El-gamal, M. (2006). *Overview of islamic finance*. *OFFICE OF INTERNATIONAL AFFAIRS OCCASIONAL*. doi:10.1037/e600342012-001

Ettouney, H., El-dessouky, H., Faibish, R. S., & Gowin, P. J. (2002). Evaluating t h e E c o n o m i c s of Desalination. *CEP Magazine*, (December), 32–39. Retrieved from http://library.certh.gr/libfiles/PDF/SPIN-172-EVALUATING-by-ETTOUNEY-in-CEP-V-98-ISS-12-PP-32-39-Y-2002.pdf

Ettouney, H., & Wilf, M. (2009). Commercial Desalination Technologies, An Overview of the Current Status of Applications of Commercial Seawater Desalination Processes. In G. Micale, L. Rizzuti, & A. Cipollina (Eds.), *Seawater Desalination* (pp. 77–107). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-01150-4

FAO. (2008). *Irrigation in the Middle East region in figures, Reporte 34*. Rome, Italy. Retrieved from ftp://ftp.fao.org/docrep/fao/012/i0936e/i0936e01.pdf

FAOSTAT. (2014). Food and Agricultural commodities production of Saudi Arabia. Retrieved January 29, 2014, from http://faostat.fao.org/DesktopDefault.aspx?PageID=339&lang=en

Farooque, a. M., Jamaluddin, A. T. M., Al-Reweli, A. R., Jalaluddin, P. a. M., Al-Marwani, S. M., Al-Mobayed, A. a., & Qasim, A. H. (2008). Parametric analyses of energy consumption and losses in SWCC SWRO plants utilizing energy recovery devices. *Desalination*, *219*(1-3), 137–159. doi:10.1016/j.desal.2007.06.004

Feldstein, M. (2013, June). Why Is US Inflation So Low - Project Syndicate. *Project-Syndicate*. Retrieved from http://www.project-syndicate.org/commentary/the-inflationary-risk-of-us-commercial-bank-reserves-by-martin-feldstein

Feo, J., Jaime Sadhwani, J., & Alvarez, L. (2013). Cost analysis in RO desalination plants production lines: mathematical model and simulation. *Desalination and Water Treatment*, *51*(25-27), 4800–4805. doi:10.1080/19443994.2013.795209

Field, A. (2013). *Discovering Statistics Using IBM SPSS Statistics* (4th Editio.). London: SAGE Publications Ltd.

Frioui, S., & Oumeddour, R. (2008). Investment and production costs of desalination plants by semi-empirical method. *Desalination*, *223*(1-3), 457–463. doi:10.1016/j.desal.2007.01.180

Fryer, J. (2010). An Investigation of the Marginal Cost of Seawater Desalination in California.

Fuller, S. K., & Petersen, S. R. (1996). *life cycle costing manual for the federal engineering Management Program*. Washington.

G20. (2013). What is the G20 _ G20. *The Group of Twenty*. Retrieved from http://www.g20.org/

Gañán, J., Rahman Al-Kassir, A., González, J. F., Macías, A., & Diaz, M. a. (2005). Influence of the cooling circulation water on the efficiency of a thermonuclear plant. *Applied Thermal Engineering*, *25*(4), 485–494. doi:10.1016/j.applthermaleng.2004.07.001

Gentle, J. E. (2003). *Random number generation and Monte Carlo methods, Statistics and computing*. (J. Chambers, W. EddY, W. Hardle, S. Sheather, & L. Tiemey, Eds.) (2nd ed.). Fairfax: Springer. Retrieved from http://books.google.com/books?hl=en&lr=&id=8sV_nuXolycC&oi=fnd&pg=PA1&dq=Random+number+generation+and+Monte+Carlo+methods&ots=x1V_gXkdSP&sig=DG_1g57Q3zuZcJRx9xVn-1ULZ7A

Gentle, J. E. (2009). *Computational Statistics*. (J. Chambbers, D. Hand, & W. Hardle, Eds.) (2009th ed., pp. 453–467). Fairfax: Springer New York. doi:10.1007/978-0-387-98144-4

Ghaffour, N., Missimer, T. M., & Amy, G. L. (2013). Technical review and evaluation of the economics of water desalination: Current and future challenges for better water supply sustainability. *Desalination*, *309*, 197–207. doi:10.1016/j.desal.2012.10.015

Giri, B. S., Karimi, I. a, & Ray, M. B. (2001). Modeling and Monte Carlo simulation of TCDD transport in a river. *Water Research*, *35*(5), 1263–79. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/11268847

Gleick, P. H. (1996). Basic Water Requirements for Human Activities : Meeting Basic Needs Basic Water Requirements for Human Activities : Meeting Basic Needs, *21*(2), 83–92.

Green, D. W., & Perry, R. H. (2007). *Perry's Chemical Engineers' Handbook* (Eighth Edi.). New York, USA: McGraw-Hill.

Greenlee, L. F., Lawler, D. F., Freeman, B. D., Marrot, B., & Moulin, P. (2009). Reverse osmosis desalination: water sources, technology, and today's challenges. *Water Research*, *43*(9), 2317–48. doi:10.1016/j.watres.2009.03.010

Haberler, G. (1960). *INFLATION, Its Causes and Cures*. Washington, DC: The American Enterprise Association.

Hagedorn, M. (2008). NOMINAL AND REAL INTEREST RATES DURING AN OPTIMAL DISINFLATION IN NEW KEYNESIAN MODEL. *WORKING PAPER SERIES, European Central Bank*, *878*(March).

Hamed, O. a. (2005). Overview of hybrid desalination systems — current status and future prospects. *Desalination*, *186*(1-3), 207–214. doi:10.1016/j.desal.2005.03.095

Hamed, O. a., & Al-Otaibi, H. a. (2010). Prospects of operation of MSF desalination plants at high TBT and low antiscalant dosing rate. *Desalination*, *256*(1-3), 181–189. doi:10.1016/j.desal.2010.01.004

Hamed, O. A., Al-sofi, M. A. K., Imam, M., Mardoup, K. B., A-mobayed, A. S., & Ehsan, A. (2000). Evaluation of polyphosphonate antiscalant at a low dose rate in the A1-Jubail Phase II MSF plant , Saudi Arabia, *I*, 275–280.

Hamoda, M. (2001). Desalination and water resource management in Kuwait. *Desalination*, *138*(1-3), 165. doi:10.1016/S0011-9164(01)00259-4

Harussi, Y., Ram, D., Galil, N., & Semiatb, R. (2009). Evaluation of membrane processes to reduce the salinity of reclaimed wastewater, *137*(2001), 71–89.

Hasan, M., & Alogeel, H. (2008). *Understanding the Inflationary Process in the GCC Region: The Case of Saudi Arabia and Kuwait*. *International Monetary Fund (IMF)Working Paper, Middle East and Central Asia Department* (Vol. 193). Retrieved from http://www.imf.org/external/pubs/ft/wp/2008/wp08193.pdf

Hauke, J., & Kossowski, T. (2011). Comparison of Values of Pearson's and Spearman's Correlation Coefficients on the Same Sets of Data. *Quaestiones Geographicae*, *30*(2). doi:10.2478/v10117-011-0021-1

Hawaidi, E. a. M., & Mujtaba, I. M. (2010). Simulation and optimization of MSF desalination process for fixed freshwater demand: Impact of brine heater fouling. *Chemical Engineering Journal*, *165*(2), 545–553. doi:10.1016/j.cej.2010.09.071

Heakal, R. (2013, July). Wh at i f Interest Rates Rise ? A Special Commentary Series what causes interest rates to rise ? *Investopedia*. Retrieved from http://www.investopedia.com/articles/03/111203.asp

Helal, A. M., Al-Malek, S. a., & Al-Katheeri, E. S. (2008). Economic feasibility of alternative designs of a PV-RO desalination unit for remote areas in the United Arab Emirates. *Desalination*, *221*(1-3), 1–16. doi:10.1016/j.desal.2007.01.064

Hilton, R. W. (2005). *Managerial Accounting, Creating Value in a Dynamic Business Enviroment* (6th ed.). New York, NY: McGraw-Hill/Irwin.

Hippel, P. Von. (2010). Skewness, *100*, 1–4. Retrieved from http://www.utexas.edu/lbj/sites/default/files/file/news/Skew.pdf

Huehmer, R., Gomez, J., Curl, J., Moore, K., & Huehmer, P. R. (2011). Cost modeling of desalination systems. In *World Congress*. Perth- Western Australia: International Desalination Association IDA.

Hussain, G., Al-Zarah, A., & Alquwaizany, A. (2010). Guidelines for irrigation water quality and water management in the Kingdom of Saudi Arabia: an overview. *Journal of Applied Sciences*, *10*(2), pp. 79–96.

InvestmentTools. (2013). Long Term T-Bond Rate. *InvestmentTools.com Web page*. Retrieved November 17, 2013, from file:///C:/27-03-2013 REPORTS/27-03-2013 RESEARCH ANALYSIS SPSS/Analysis/paper Cost/Inflation and Interest rate/long_term_t_bond_rate.htm

Irving, I., Querns, W. R., & Steward, D. (2008). *WT Cost II Modeling the Capital and Operating Costs of Thermal Desalination Processes Utilizing a Recently Developed Computer Program that Evaluates Membrane Desalting , Electrodialysis , and Ion Exchange Plants*. Denver, USA.

JMC. (2013). Wh at i f Interest Rates Rise ? A Special Commentary Series what causes interest rates to rise ? *Janney Montgomery Scott LLC*. Retrieved February 08, 2014, from http://www.janney.com/individuals--families/resources--education/research--insights/interest-rates

Kamal, I. (2008). Myth and reality of the hybrid desalination process. *Desalination*, *230*(1-3), 269–280. doi:10.1016/j.desal.2007.11.030

Kannan, R., Tso, C. ., Osman, R., & Ho, H. . (2004). LCA–LCCA of oil fired steam turbine power plant in Singapore. *Energy Conversion and Management*, *45*(18-19), 3093–3107. doi:10.1016/j.enconman.2004.01.005

Kaplan, R., & Cooper, R. (1998). *Cost & Effect: Using Integrated Cost Systems to Drive Profitability and Performance* (1st ed.). Harvard Business Review Press.

Karagiannis, I. C., & Soldatos, P. G. (2008). Water desalination cost literature: review and assessment. *Desalination*, *223*(1-3), 448–456. doi:10.1016/j.desal.2007.02.071

KAUST. (2011). *The KICP Annual Strategic Study, Promoting Wastewater Reclamation and Reuse in the Kingdom of Saudi Arabia :Technology Trends, Innovation Needs, and Business Opportunities*. Rabigh saudi arabia.

Kavvadias, K. C., & Khamis, I. (2010). The IAEA DEEP desalination economic model: A critical review. *Desalination*, *257*(1-3), 150–157. doi:10.1016/j.desal.2010.02.032

Kelly, J. R., & Male, S. (1993). *VALUE MANAGEMENT IN DESIGN AND CONSTRUCTION* (1st Editio.). New York, NY: Chapman & Hall, Incorporated.

Khan A.H. (1986). *Desalination Processes and Multistage Flash Disalination Practice*. Amstrdam, The Netherlands: Elsevier Science Publisher B.V.

Khawaj, A. D., & Wie, J. (2001). Performance of MSF desalination plant components over fifteen years at Madinat Yanbu A1-Sinaiyah, *134*(November 2000), 231–239.

Khawaji, A., Kutubkhanah, I., & Wie, J.-M. (2008). Advances in seawater desalination technologies. *Desalination*, *221*(1-3), 47–69. doi:10.1016/j.desal.2007.01.067

Khayet, M. (2013). Solar desalination by membrane distillation: Dispersion in energy consumption analysis and water production costs (a review). *Desalination*, *308*, 89–101. doi:10.1016/j.desal.2012.07.010

Kim, Y. M., Lee, Y. S., Lee, Y. G., Kim, S. J., Yang, D. R., Kim, I. S., & Kim, J. H. (2009). Development of a package model for process simulation and cost estimation of seawater reverse osmosis desalination plant. *Desalination*, *247*(1-3), 326–335. doi:10.1016/j.desal.2008.12.035

Kishk, M., Al-Hajj, A., & Pollock, R. (2003). Whole life costing in construction-A state of the art review. *RICS Foundation …*, *4*(18). Retrieved from http://usir.salford.ac.uk/id/eprint/12966

Kottegoda, N. T. (1980). *Stochastic Water Resources Technology* (p. 136). London: The machmillian press LTD.

Lamei, a., van der Zaag, P., & von Münch, E. (2008). Basic cost equations to estimate unit production costs for RO desalination and long-distance piping to supply water to tourism-dominated arid coastal regions of Egypt. *Desalination*, *225*(1-3), 1–12. doi:10.1016/j.desal.2007.08.003

Lomax, I. (2009a). The Pace of Change in Seawater Desalination by Reverse Osmosis. In R. I. Prof. Asit K. Biswas,Tortajada, Cecilia L (Ed.), *Water Management in 2020 and Beyond* (pp. 251–258). Berlin Heidelberg: Springer Berlin Heidelberg. Retrieved from http://download.springer.com/static/pdf/864/chp%3A10.1007%2F978-3-

540-89346-2_13.pdf?auth66=1391716390_931ae9c8d0bacb2e6b3b161b1894c158&ext=.pdf

Lomax, I. (2009b). The pace of change in seawater desalination by reverse osmosis. In D. Altinbilek, C. Gopalakrishnan, J. Lundqvist, A. Pres, A. Turton, & O. Varis (Eds.), *Water Management in 2020 and Beyond*. Mexico: ?Springer-Verlag Berlin Heidelberg 2009 c This. Retrieved from http://link.springer.com/chapter/10.1007/978-3-540-89346-2_13

Ludwig, H. (2004). Hybrid systems in seawater desalination- practical design aspects, present status and development perspectives, *164*(May 2003), 1–18.

Mayer, D. G., & Butler, D. G. (1993). Statistical validation. *Ecological Modelling*, *68*(1-2), 21–32. doi:10.1016/0304-3800(93)90105-2

McGinnis, R. L., & Elimelech, M. (2007). Energy requirements of ammonia–carbon dioxide forward osmosis desalination. *Desalination*, *207*(1-3), 370–382. doi:10.1016/j.desal.2006.08.012

McGivney, W., & Kawamura, S. (2008). *Cost Estimating Manual for Water Treatment Facilities*. Hoboken, NJ, USA: John Wiley & Sons, Inc. doi:10.1002/9780470260036

McLeod, a. I. (1993). Parsimony, Model Adequacy and Periodic Correlation in Time Series Forecasting. *International Statistical Review / Revue Internationale de Statistique*, *61*(3), 387. doi:10.2307/1403750

McMahon, T. A., & Adeloye, A. J. (2005). *Water Resources Yield* (p. 220). Water Resources Publication. Retrieved from http://books.google.com/books?id=XzLfvSylIWUC&pgis=1

McMahon, T. A., & Mein, R. G. (1986). *River and Reservoir Yield* (1st ed.). Littleton, Colorado, USA: Water Resources Publications.

McMahon, T. A., & Miller, A. J. (1971). Applicatin of Thomas and Fiering Mdel to Skewed Hydrlogic Data. *Water Resources Management*, *7*(5), 1338.

MEP. (2010). *The Ninth Development Plan (2010–2014), Water and sanitation* (p. Ch–5). Riyadh, Saudi Arabia. Retrieved from http://www.mep.gov.sa/themes/GoldenCarpet/index.jsp#1391109482548

MEP. (2013). LONG-TERM STRATEGY FOR THE SAUDI ECONOMY. *Ministry of Economy and Planning in the Kingdom of Saudi Arabia*. Retrieved July 13, 2013, from http://www.mep.gov.sa/index.jsp;jsessionid

MF. (2013). The general budget of the Kingdom of Saudi Arabia saudi, Ministry of finance. *Ministry of finance*. Retrieved November 22, 2013, from http://www.mof.gov.sa/english/Pages/Home.aspx

Micale, G., Cipollina, A., & Rizzuti, L. (2009). Seawater Desalination for Freshwater Production. In A. Cipollina, G. Micale, & L. Rizzuti (Eds.), *seawater desalination conventional and renewable energy processes* (1st ed., pp. 1–15). Berlin, Heidelberg: Springer Berlin Heidelberg. doi:10.1007/978-3-642-01150-4

Montaseri, M., & Adeloye, a. . (1999). Critical period of reservoir systems for planning purposes. *Journal of Hydrology*, *224*(3-4), 115–136. doi:10.1016/S0022-1694(99)00126-2

Motulsky, H., & Christopoulos, A. (2003). *Fitting Models to Biological Data using Linear and Nonlinear Regression* (2nd ed.). SanDiego CA: GraphPad Software.

Musgrave, R. A., & Musgrave, P. B. (1989). *Public Finance in Theory and Practice* (5th Editio.). Singapore: McGraw-Hill Book Co.

MWE. (2013a). Ministry of water and electricity; our partners. *Ministry of water and electricity in Saudi Arabia*. Retrieved from http://www.mowe.gov.sa/

MWE. (2013b). *Wastewater treatment in saudi arabia 2012*. Riyadh, Saudi Arabia.

MWE. (2013c). *Water in the Kingdom of Saudi Arabia in 2012*. Riyadh, Saudi Arabia. Retrieved from http://www.mowe.gov.sa/files/forms/Water2012/Water2012.html#/1/

MWE. (2014a). *Flood Protection and harvest more rain in Saudi Arabia, 2013*. Riyadh, Saudi Arabia. Retrieved from http://www.mowe.gov.sa/Arabic/PDF/السدود/index.html

MWE. (2014b). Wastewater treatment plan 2010-2025. *Ministry of water and electricity in Saudi Arabiainistry of water and electricity saudi arabia*. Retrieved January 25, 2014, from http://www.mowe.gov.sa/

Nadaa, N. A., Zahranib, A., & Ericssonc, B. (1987). Experience on pre- and post-treatment from sea water desalination plants in Saudi Arabia. *Desalination*, *66*, 303–318.

Niederreiter, H. (1992). *Random Number Generation and Quasi-Monte Carlo Methods (CBMS-NSF Regional Conference Series in Applied Mathematics)*. Society for Industrial and Applied Mathematics.

NWC. (2013). About National Water Company (NWC). Retrieved from http://www.nwc.com.sa/English/Pages/default.aspx

Pankratz, T. (2010). *IDA desaliantion Year book “2009-2010”, Water Desalination Report*. Oxford, UK.

Pankratz, T. (2013). *IDA desaliantion Year book “2012-2013”, Water Desalination Report*. (R. Owen, Ed.). Oxford, UK: Media Anlytics Ltd, The Jam Factory.

Parks, J., & President, V. (2002). Alternatives to the 30-Year Treasury Rate A Public Statement by the Pension Practice Council of the American Academy of Actuaries.

Pilat, B. (2001). Practice of water desalination by electrodialysis. *Desalination*, *139*(1-3), 385–392. doi:10.1016/S0011-9164(01)00338-1

Pontié, M., Rapenne, S., Thekkedath, A., Duchesne, J., Jacquemet, V., Leparc, J., & Suty, H. (2005). Tools for membrane autopsies and antifouling strategies in seawater feeds: a review. *Desalination*, *181*(1-3), 75–90. doi:10.1016/j.desal.2005.01.013

Prihasto, N., Liu, Q.-F., & Kim, S.-H. (2009). Pre-treatment strategies for seawater desalination by reverse osmosis system. *Desalination*, *249*(1), 308–316. doi:10.1016/j.desal.2008.09.010

Rabie, O. (2008). *Statistical analysis of multi variables by using spss* (1st editio.). Cairo: Minufiya University.

Raluy, R. G., Serra, L., Uche, J., & Valero, a. (2004). Life-cycle assessment of desalination technologies integrated with energy production systems. *Desalination*, *167*, 445–458. doi:10.1016/j.desal.2004.06.160

Raouf, M. A. (2009). Water Issues in the Gulf: Time for Action. *The Middle East Institute Policy Brief*, *22*(1), 24. doi:10.1177/0022146513479002

Rasmala. (2011). *Qatar Electric & Water Co . Where to now ? Rasmala*. Dubai, UAE. Retrieved from http://www.rasmala.com/equity_report/qatar_electric_water_co_05oct11.pdf

Rebort, C. P., & Casella, G. (2004). *Monte Carlo statistical method* (2nd Editio.). Uinversity of Florida, USA: Springer texts in statistics.

RESAW. (2013). The Royal Embassy of Saudi Arabia Homepage. *The Royal Embassy of Saudi Arabia in washington DC Homepage,*. Retrieved from http://www.saudiembassy.net/

Roberts, D. a, Johnston, E. L., & Knott, N. a. (2010). Impacts of desalination plant discharges on the marine environment: A critical review of published studies. *Water Research*, *44*(18), 5117–28. doi:10.1016/j.watres.2010.04.036

Rogers, C. S., Sturdivant, A. W., Rister, M. E., Lacewell, R. D., & Harris, B. L. (2008). Economic Implications of Conventional Water Treatment Versus Desalination: A Dual Case Study. In *the Southern Agricultural Economics Association Annual Meeting*. Dallas, Texas USA: the Southern Agricultural Economics Association Annual Meeting, Dallas, TX, February 2-6, 2008 Copyright. Retrieved from http://ageconsearch.umn.edu/bitstream/6729/2/sp08ro14.pdf

Rustum, R., & Adeloye, A. J. (2007). Replacing Outliers and Missing Values from Activated Sludge Data Using Kohonen Self-Organizing Map. *Journal of Environmental Engineering*, *133*(September), 909–916.

SAMA. (2008). *Annual Report 43 (2007)*. Riyadh, Saudi Arabia.

SAMA. (2011). *Annual Report 47 (2010)*. Riyadh, Saudi Arabia.

Schade, J. (2007). LIFE CYCLE COST CALCULATION MODELS FOR BUILDINGS. In B. Atkin & B. Jan (Eds.), *Proceedings of 4th Nordic Conference on Construction Economics and Organisation : Development Processes in Construction Mangement* (pp. 321–329). Luleå-Sweden: Luleå tekniska universitet. Retrieved from http://www.inpro-project.eu/media/lcc_juttaschade.pdf

SDWF. (2013). *ULTRAFILTRATION , NANOFILTRATION AND REVERSE* (pp. 1–6). Saskatoon, Canada.

Sharp, A. M., & Olson, K. W. (1978). *Public Finance " The economics of government revenues and expenditures"* (1st Editio.). Minnesota, USA: West Publishing Co.

Shatat, M., Worall, M., & Riffat, S. (2013). Opportunities for solar water desalination worldwide: Review. *Sustainable Cities and Society*, *9*, 67–80. doi:10.1016/j.scs.2013.03.004

Silva, A. T. (2010). *Design of the storage capacity of artificial reservoirs*. Instituto Superior Técnico, Technical University of Lisbon, Lisbon, Portugal.

Silva, A. T., & Portela, M. M. (2012). Disaggregation modelling of monthly streamflows using a new approach of the method of fragments. *Hydrological Sciences Journal*, *57*(5), 942–955. doi:10.1080/02626667.2012.686695

Sommariva, C. (2010). *Desalination and Advance Water Treatment Economics and Financing* (p. 168). Hopkinton, USA: Balaban Publishers. Retrieved from http://www.amazon.com/Desalination-Advance-Treatment-Economics-Financing/dp/0866890696

Srikanthan, R., & McMahon, T. A. (1982). Stochastic generation of monthly streamflow. *Journal of the Hydraulics Division Proceedings of the American Society of Civil Engineers, ASCE, 108*(3), 419–44.

Srikanthan, R., & McMahon, T. a. (2001). Stochastic generation of annual, monthly and daily climate data: A review. *Hydrology and Earth System Sciences*, *5*(4), 653–670. doi:10.5194/hess-5-653-2001

Srikanthan, R., McMahon, T., & Sharma, A. (2002). *CATCHMENT HYDROLOGY STOCHASTIC GENERATION OF MONTHLY RAINFALL DATA, TECHNICAL REPORT*.

Stedinger, J. R., Vogel, R. M., & Foufoula-Georgiou, E. (1993). Frequency analysis of extreme events. In D. R. Maidment (Ed.), *Handbook of Applied Hydrology*. NY, USA: McGraw-Hill.

Stover, R. L. (2004). Development of a fourth generation energy recovery device. A "CTO"s notebook'. *Desalination*, *165*, 313–321. doi:10.1016/j.desal.2004.06.036

Sullivn, W. G., Wicks, E. M., & Luxhoj, J. T. (2003). *Engineering Economy* (12th ed.). pper Saddle River, N.J. : London: Prentice Hall ; Prentice-Hall International.

SUSRIS. (2013). Saudi Arabia provinces. *Saudi-US Relations Information Service*. Retrieved from http://susris.com/

SWCC. (2006). *Desalination history in Saudi Arabia* (1st ed.). Riyadh, Saudi Arabia: SWCC. Retrieved from http://www.swcc.gov.sa/

SWCC. (2009). *Saline Water Conversion Corporation (SWCC), Annual report No. 35 (2008)*. Riyadh, Saudi Arabia.

SWCC. (2010). *Saline Water Conversion Corporation (SWCC), Annual report No.36 (2009)*. Riyadh, Saudi Arabia.

SWCC. (2011). *Saline Water Conversion Corporation (SWCC), Annual report No. 37 (2010)*. Riyadh, Saudi Arabia.

SWCC. (2013a). About Saline Water Conversion Corporation. *Saline Water Conversion Corporation*. Retrieved October 22, 2013, from http://www.swcc.gov.sa/

SWCC. (2013b). *Saline Water Conversion Corporation (SWCC), Annual report No. 39 (2012)*. Riyadh, Saudi Arabia.

TE. (2013). TRADING ECONOMICS _ 300. *trading economics*. Retrieved from http://www.tradingeconomics.com/

TFSA. (2013). Guidelines for the Evaluation of Public Sector Initiatives. *Department of Treasury and Finance, Government of South Australian*. Retrieved September 02, 2013, from http://www.treasury.sa.gov.au/__data/assets/pdf_file/0004/1768/TI17-guidelines.pdf

UN. (2011). *World Population Prospects The 2010 Revision*. *United Nations New York, 2011* (Vol. I). New York, USA. Retrieved from http://esa.un.org/wpp/Documentation/pdf/WPP2010_Volume-I_Comprehensive-Tables.pdf

US Inflation, C. (2014). US Inflation rate (%). *US Inflation Calculator*. Retrieved from http://www.usinflationcalculator.com/inflation/historical-inflation-rates/

USDT. (2012). Historical treasury Yield Curve Rates. *The Department of the Treasury's Data Center, USA*. Retrieved October 09, 2012, from http://www.treasury.gov/Pages/default.aspx

Usmani, M. M. T. (2002). *An Introduction to Islamic Finance* (p. 48). Karachi, pakistan: Maktaba Ma'Ariful Wuran.

Waston, I., Morin, O., & Henthorne, L. (2003). *Desalting Handbook For Planners* (Third Edit.). U.S. Department of the Interior, Bureau of Reclamation Technical Service Center Water Treatment Engineering and Research Group Cooperative Assistance Agreement Numbe.

WB. (2014). Introduction to Wastewater Treatment Processes World Bank – Water. The world bank. Retrieved from file:///F:/Wastewater/Introduction to Wastewater Treatment Processes World Bank – Water.htm

WDR. (2014). Freeze Desalination a look back _ Desalination. *Water Desalination Report (WDR).Desalination.com*. Desalination.com. Retrieved January 04, 2014, from http://www.desalination.com/wdr/49/27/freeze-desalination-look-back

Wilson, R. (2007). Arab Government Responses to Islamic Finance : The Cases of Egypt and Saudi Arabia Arab Government Responses to Islamic Finance : The Cases of Egypt and, (October 2012), 37–41.

Wittholz, M. K., O'Neill, B. K., Colby, C. B., & Lewis, D. (2008). Estimating the cost of desalination plants using a cost database. *Desalination*, *229*(1-3), 10–20. doi:10.1016/j.desal.2007.07.023

Wolf, P. H., Siverns, S., & Monti, S. (2005). UF membranes for RO desalination pretreatment. *Desalination*, *182*(1-3), 293–300. doi:10.1016/j.desal.2005.05.006

Younos, T. (2005a). The Economics of Desalination. *JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION*, *132*(1), 39–45.

Younos, T. (2005b). The Economics of Desalination. *JOURNAL OF CONTEMPORARY WATER RESEARCH & EDUCATION*, *132*(1), 39–45.

Zawad, F. M. Al. (2008). Impacts of Climate Change on Water Resources in Saudi Arabia. The 3rd International Conference on Water Resources and Arid Environments (2008) and the 1st Arab Water Forum.

Zhou, Y., & Tol, R. S. J. (2004). Implications o f desalination for water resources in China - - an e c o n o m i c perspective, *164*, 225–240.

Zhou, Y., & Tol, R. S. J. (2005). Evaluating the costs of desalination and water transport. *Water Resources Research*, *41*(3), n/a–n/a. doi:10.1029/2004WR003749

Appendixes (in the attached CD)

- **Appendix A** Original collected data
- **Appendix B** Results of method of fragment
- **Appendix C** Results of the energy consumption
- **Appendix D** Final data used for cost models development
- **Appendix E** Frequency distribution comparison before and after applying the Box-Cox method
- **Appendix F** Statistical parameters comparison between historical and generated data
- **Appendix G** Whiskers and box plot diagrams comparison between historical and generated data
- **Appendix H** Equivalent annual cost on different r values